The University of Minnesota / NASA

Validation of US3D for Capsule Aerodynamics using 05-CA Wind Tunnel Test Data

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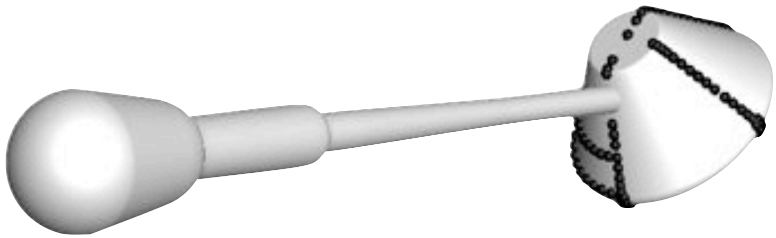
11/19/12

Outline of Presentation



Motivation

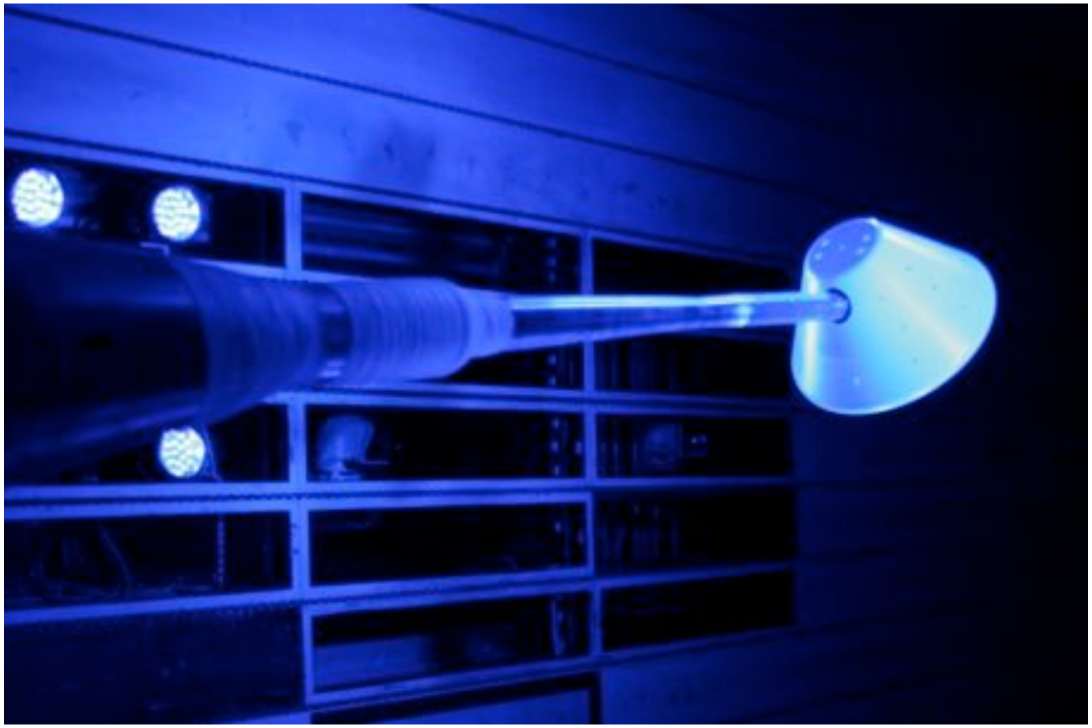
05-CA Overview

Numerical Inputs - Solver, Method, Grid

Sensitivity Analysis - Spacial, Temporal

Results

- Integrated Aerodynamic Loads
- Pressure Port Comparisons
- Possible improvements



Conclusions

Questions

Motivation

NASA is currently investigating and has a long history of employing capsule shapes for a variety of missions - manned and unmanned.

In order to design the most efficient system possible, correct characterization of the vehicle's aerodynamics are imperative.

- Parachute Mass
- Structural Loading
- Downrange Concerns

Historically, a combination of wind tunnel testing and flight testing has been most useful. Computational Fluid Dynamics (CFD) are becoming an increasingly vital piece of this work, though.

Current models employed at NASA still allow for a large degree of uncertainty in aerodynamic prediction. There is room for new tools to assist in design decisions.

US3D continues to improve the state of the science and is beginning to see use in aerodynamic prediction for capsule shapes. This work is designed to:

- Help understand how applicable the code is to these shapes
- Provide suggestions on best practices
- Outline avenues for improvement and areas of greatest confidence

05-CA Overview

05-CA was a wind tunnel test performed in two NASA Ames test sections:

- 9-foot x 7-foot supersonic test section : Mach 1.6 - Mach 2.5
- 11-foot transonic test section : Mach 0.3 - Mach 1.4

This work will focus on the 11-foot section and a 7.66% model.

- Model was heavily instrumented and provides the largest wealth of validation data.
  - 151 pressure ports with static measurements
  - 6-axis balance for integrated loads
  - 12 unsteady pressure transducers
- Wide range of Mach number and Angle of Attack (α) available for comparison.

α \ Mach	0.3	0.5	0.6	0.7	0.8	0.9	0.95	1.05	1.1	1.2	1.4
140		x					x				x
145											
150											
155		x					x				x
160											
165											
170		x					x				x

A supersonic, transonic, and subsonic case were considered at three angles of attack in order to provide an initial look at how US3D's performance varied between these three regimes.

Flow Solver - US3D

US3D is an unstructured, finite-volume CFD code developed at the University of Minnesota. It is fully-parallel and implicit.

- Steiger-Warming flux vector splitting
- Differed-Correction approach to viscous fluxes
- Includes both RANS and LES turbulence modeling
- Detached Eddy Simulation (DES) also fully supported
- 2nd-order implicit Euler time advancement
- Low dissipation numerics (CITE)

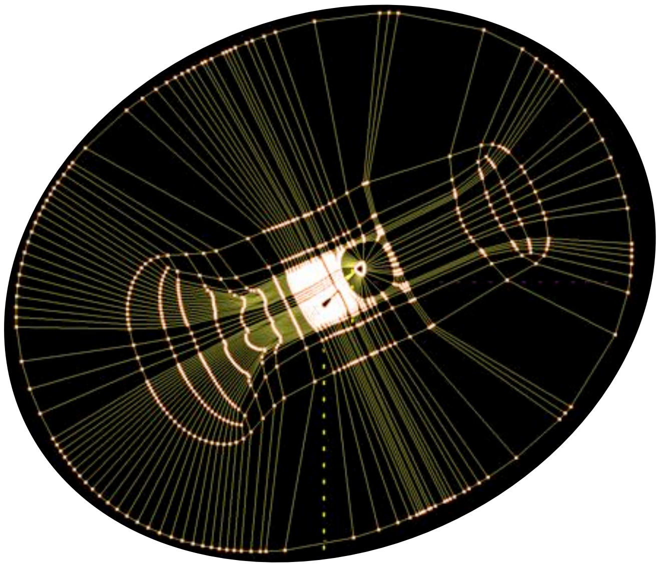
High-order and low dissipation allow for superior computations. Additionally, combined RANS/LES simulations (DES) provide much higher fidelity in the wake region - a major driver for this problem's aerodynamics.

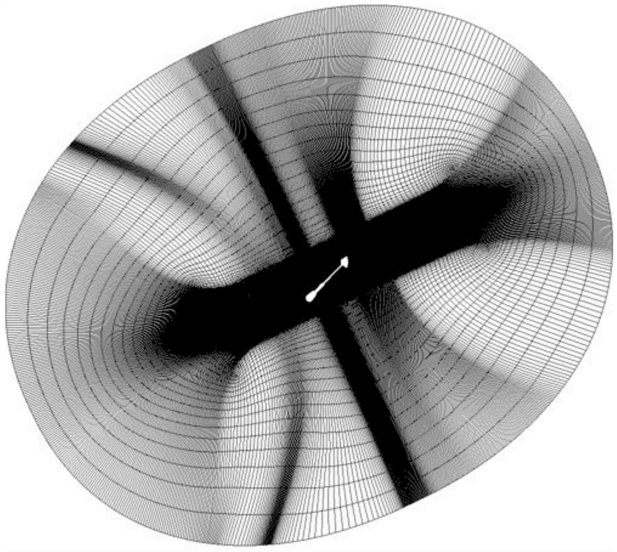
Going to compare three numerical methods in US3D:

- RANS turbulence model
- DES turbulence model with Steiger-Warming dissipative fluxes
- DES turbulence model with low-dissipation kinetic energy conserving fluxes

Grid Generation

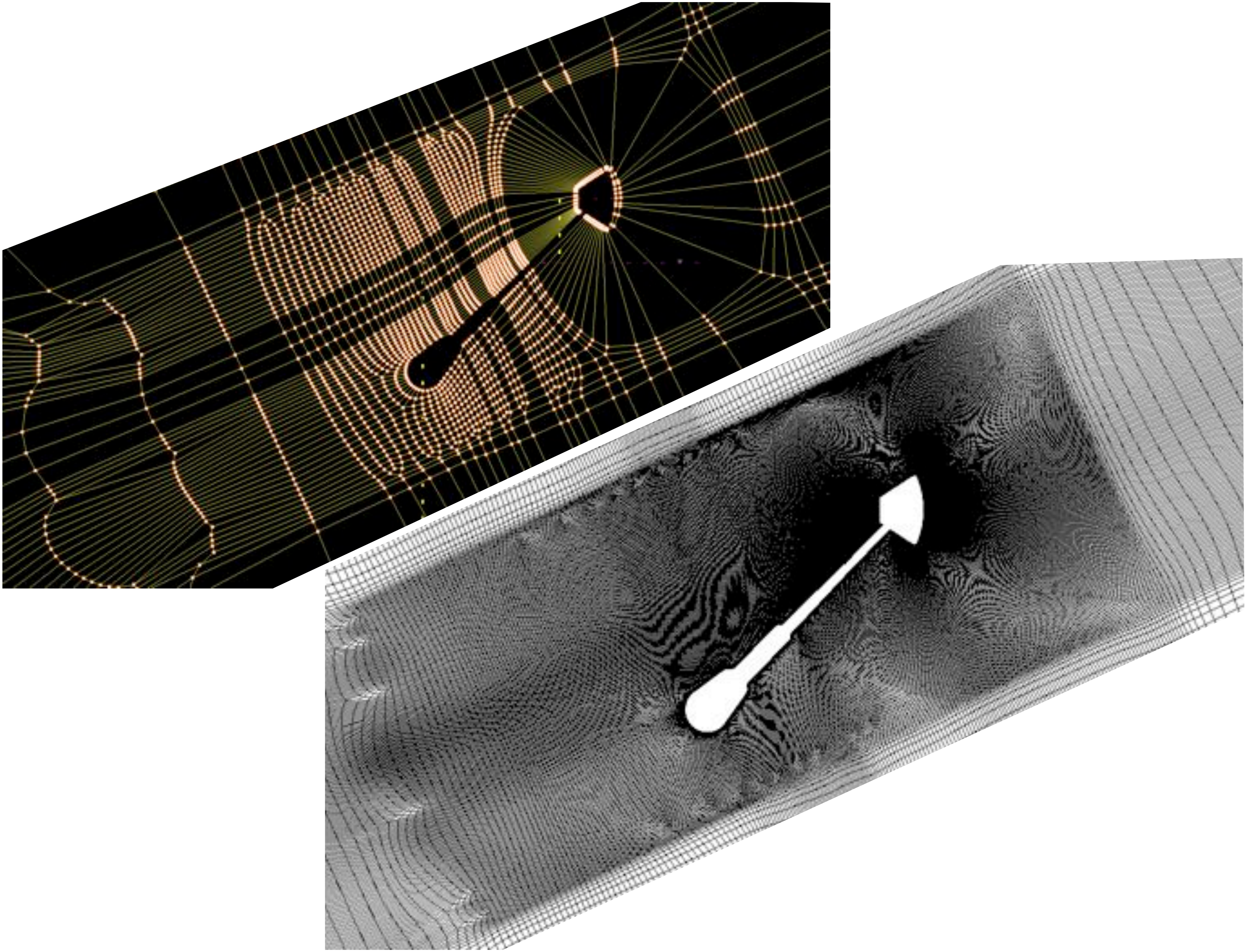
All grid generation was performed with GridPro..

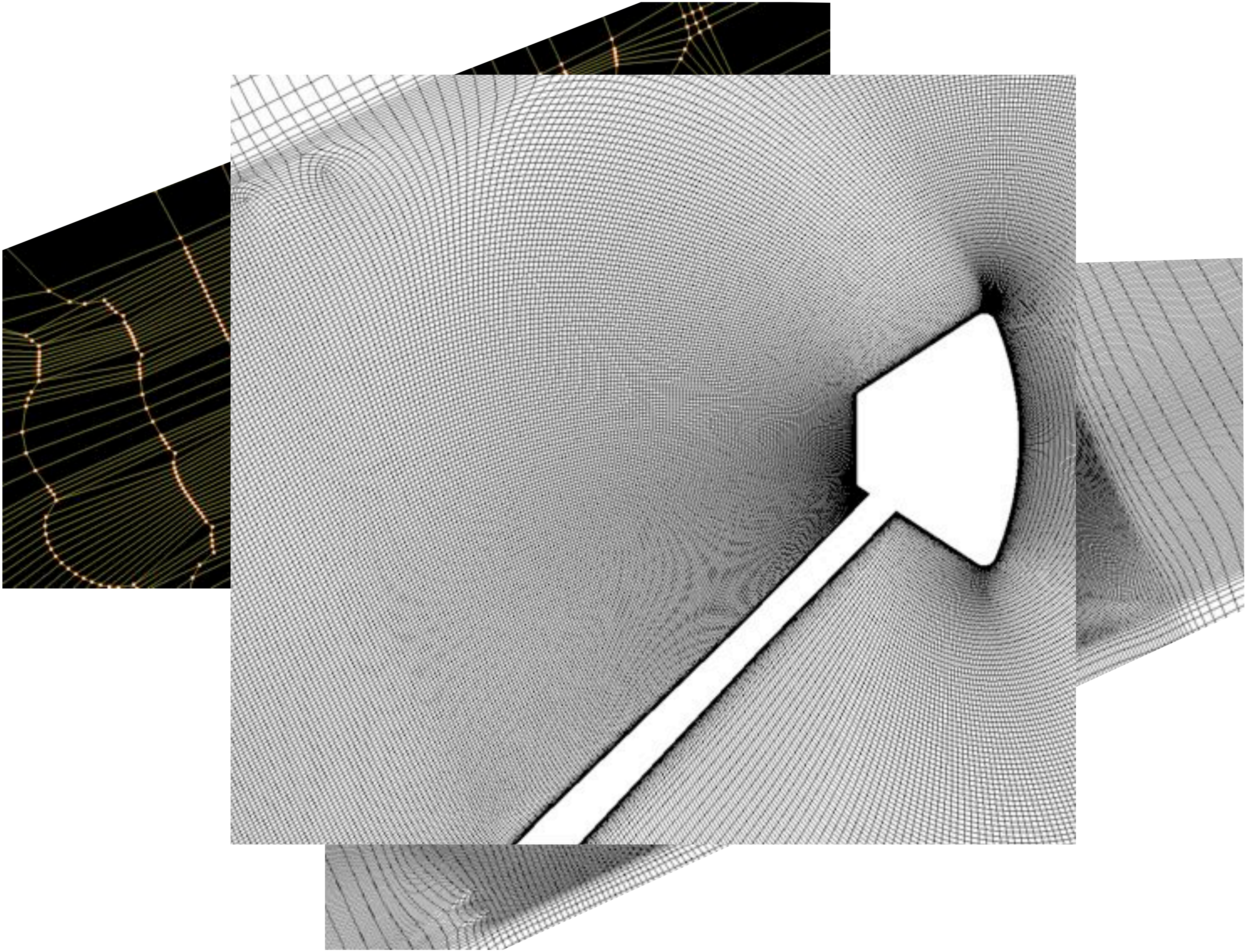




Some important notes and features:

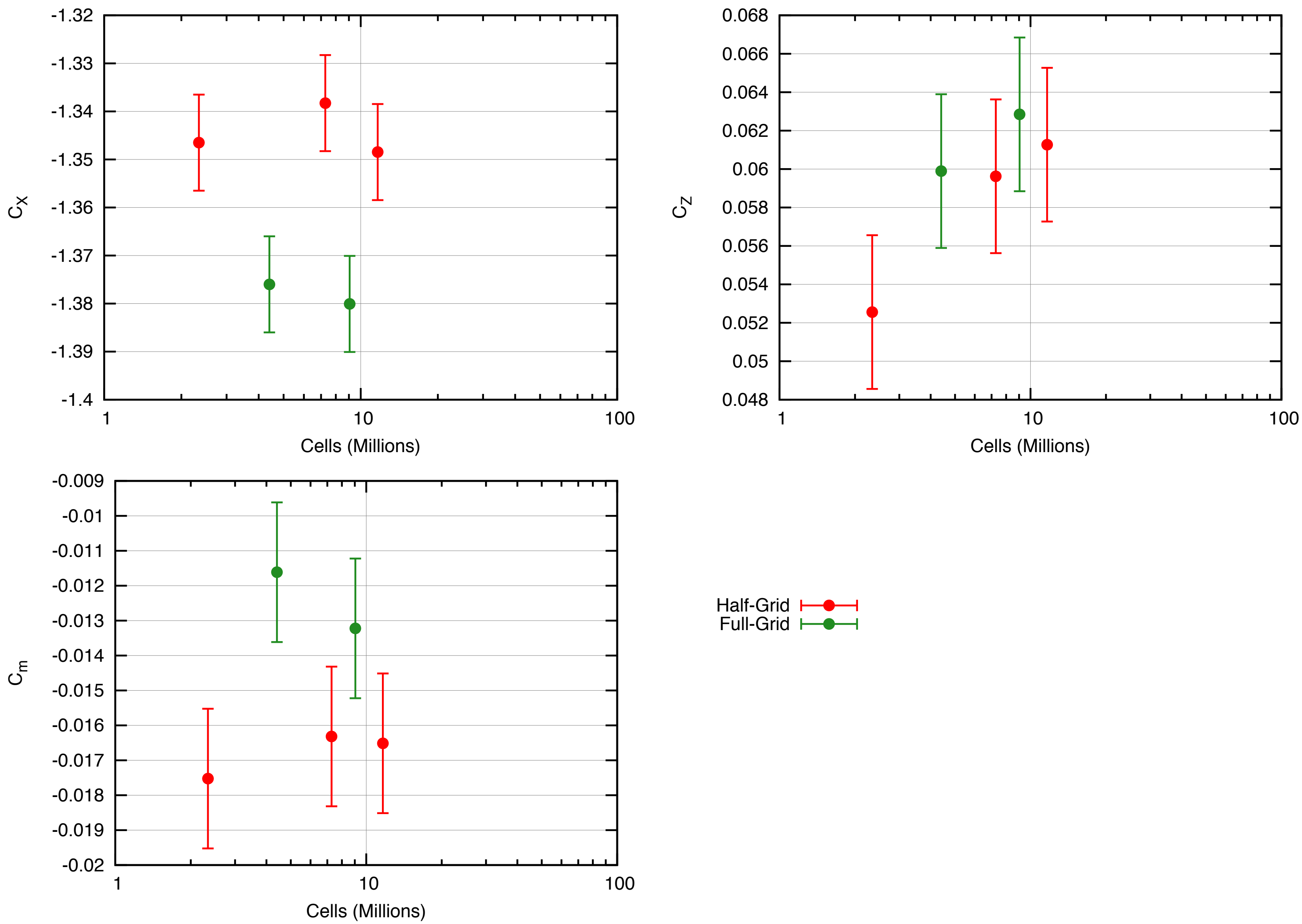
- A portion of the sting was included to improve computational fidelity.
- Wind tunnel walls were not modeled.
- Extensive smoothing iterations were applied in order to drive the grid smoother to a steady-state. This helped maintain similarity between grids of different resolutions.
- Wake refinement was aligned with the mid-α case in order to best capture the range of the analysis. It extended 6 diameters downstream - a distance selected based on best practices used by NASA for similar computations using OVERFLOW (CITE).
- Similarly, the outer boundaries extended 30 diameters from the vehicle in order to minimize their effect for the subsonic cases.
- Viscous wall-spacing selected to maintain y^+ of less than 1 on entire geometry.





Grid Resolution Study

One of the first analysis performed was an investigation into the spacial refinement and its effect on the quantity of interest, aerodynamic loads.

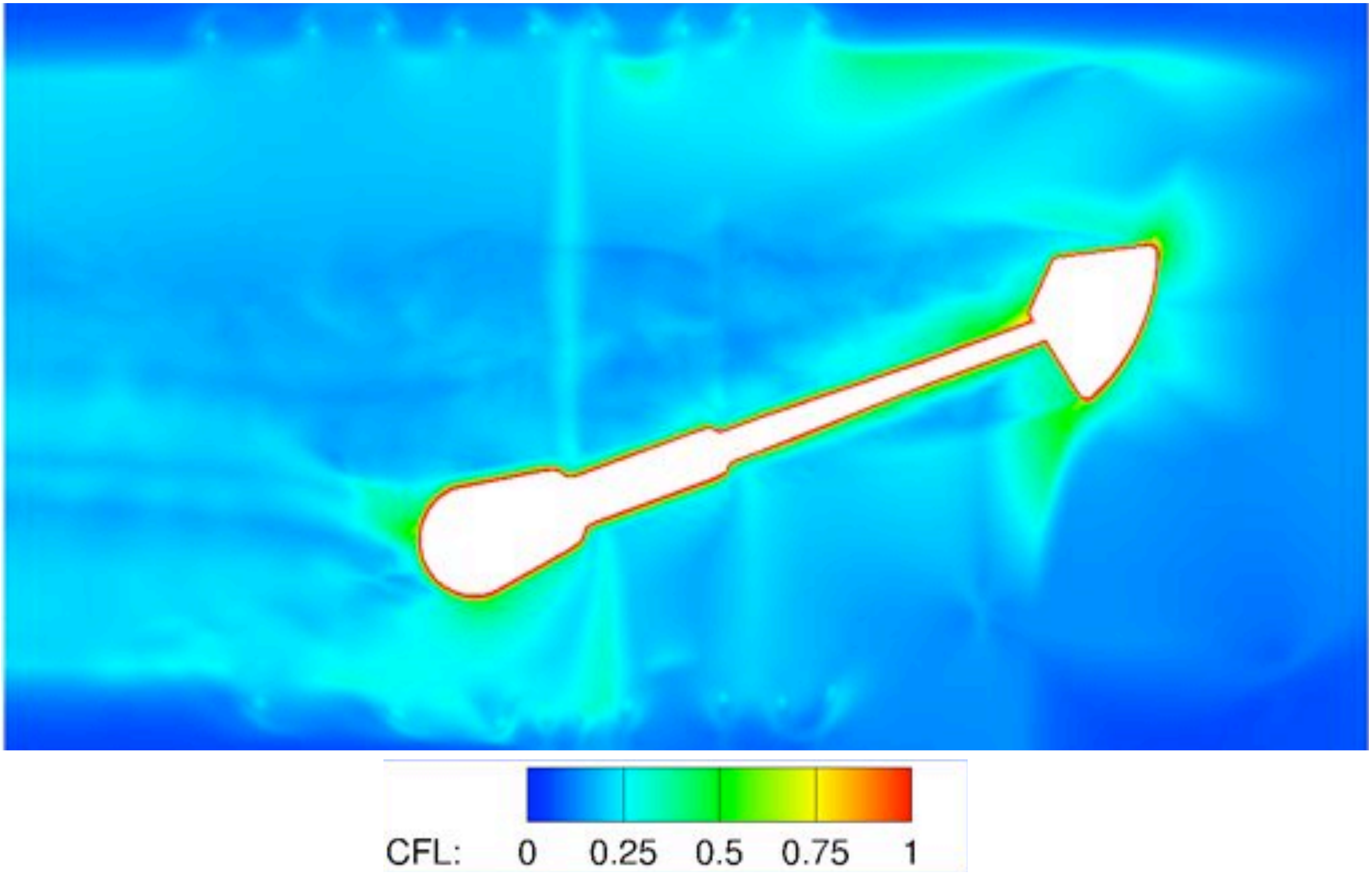


Final grid of 18,217,949 points and 18,113,216 cells.

Temporal Resolution Study

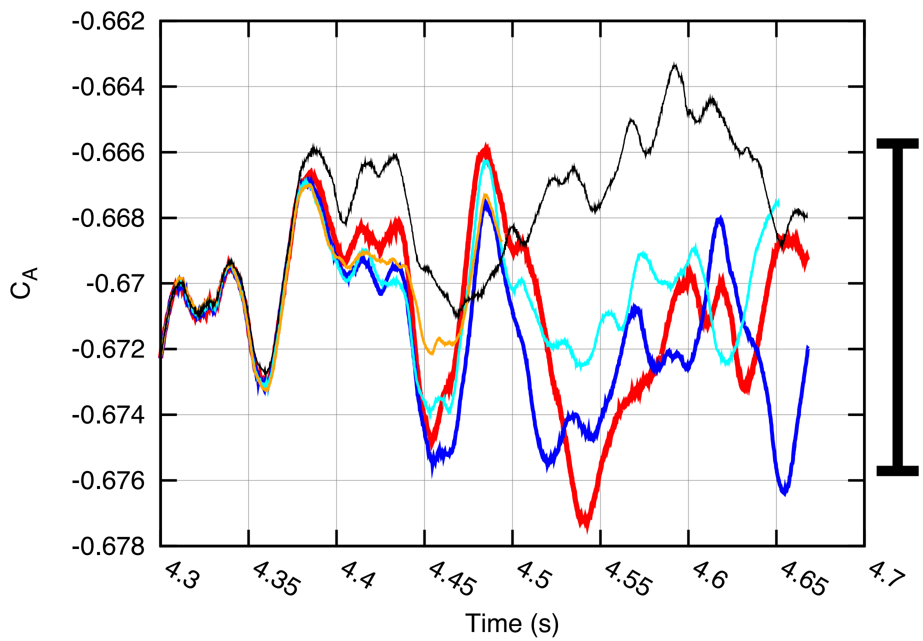
Just as significant to the validity of the results is the selection of the proper timestep to use for these simulations.

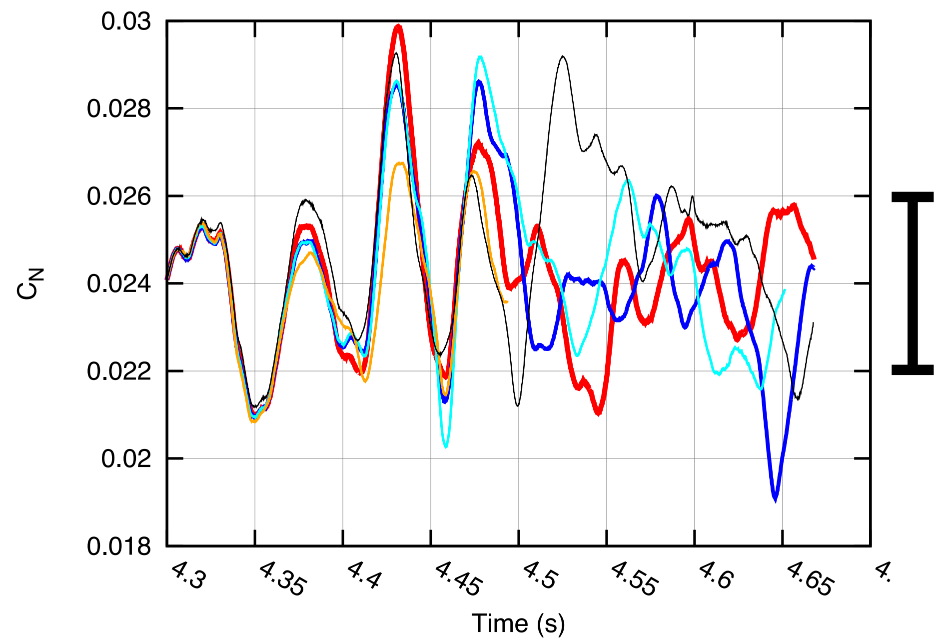
- One initial consideration was to maintain a CFL of less than 1 throughout the wake region. Maximum CFL values varied for each Mach number.

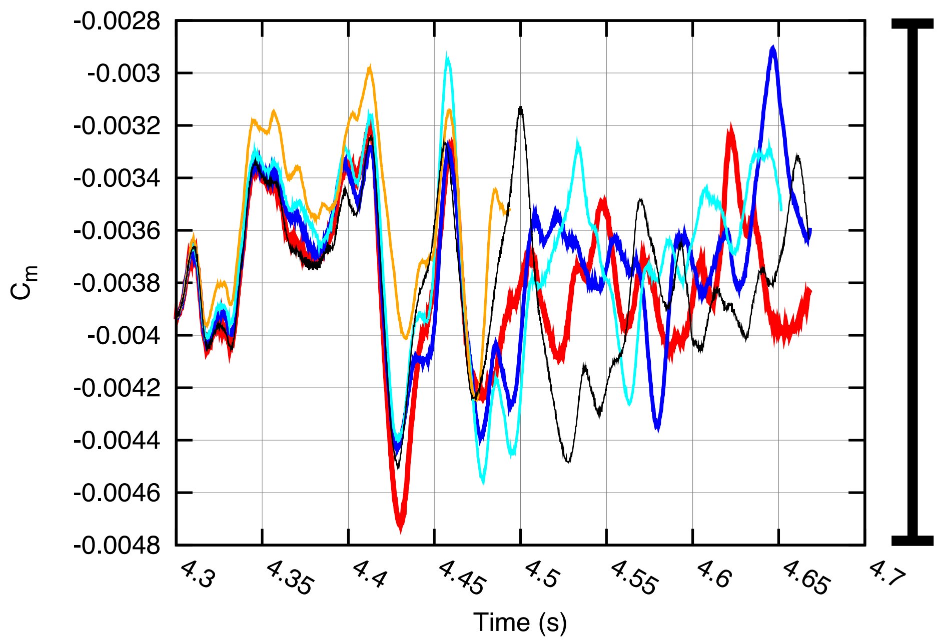


Temporal Resolution Study

Also of concern was the effect on the integrated forces and moments.







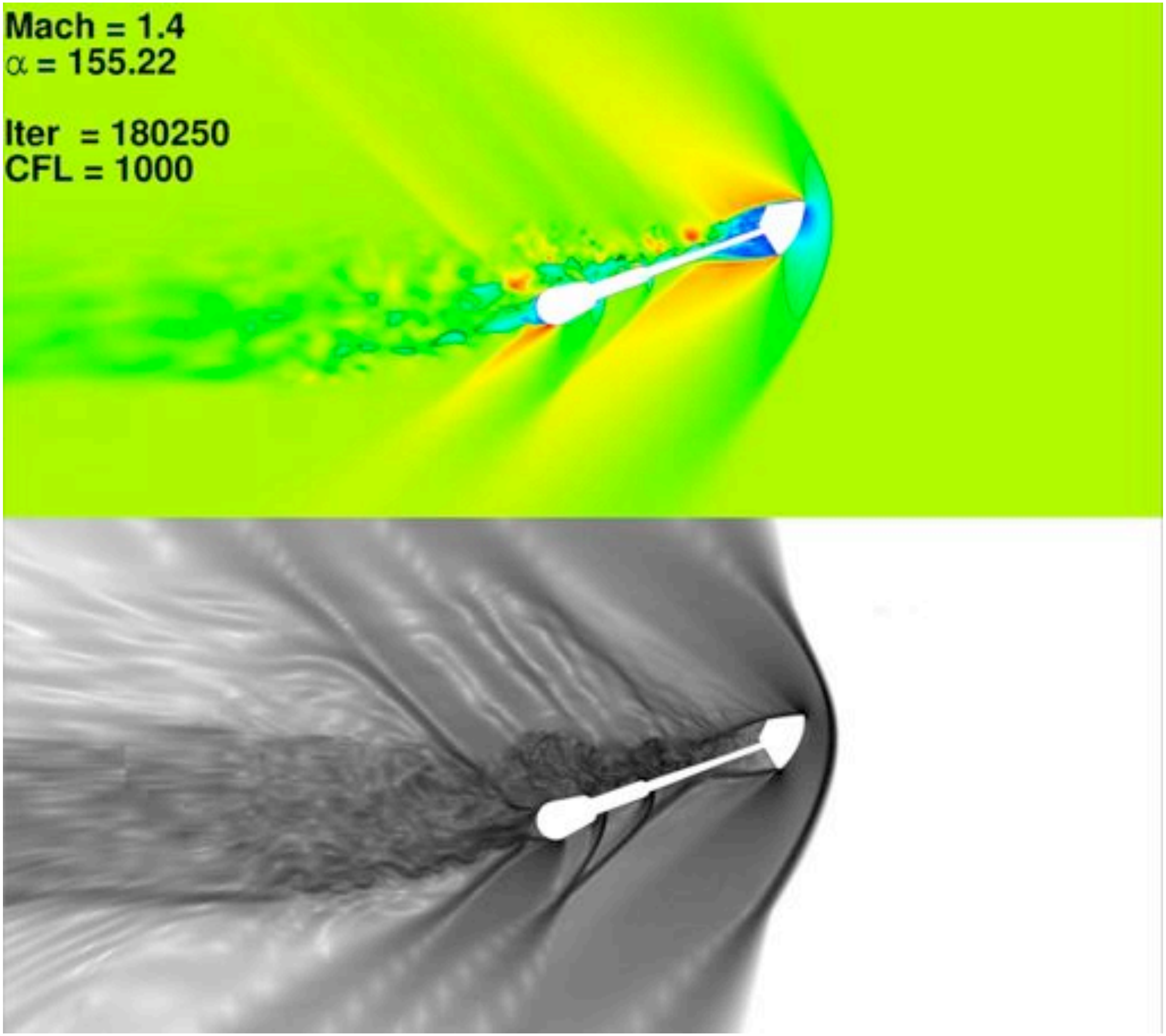
Diverge at 4.31 seconds

1000
500
250
100
2000

Results

Mach 1.40

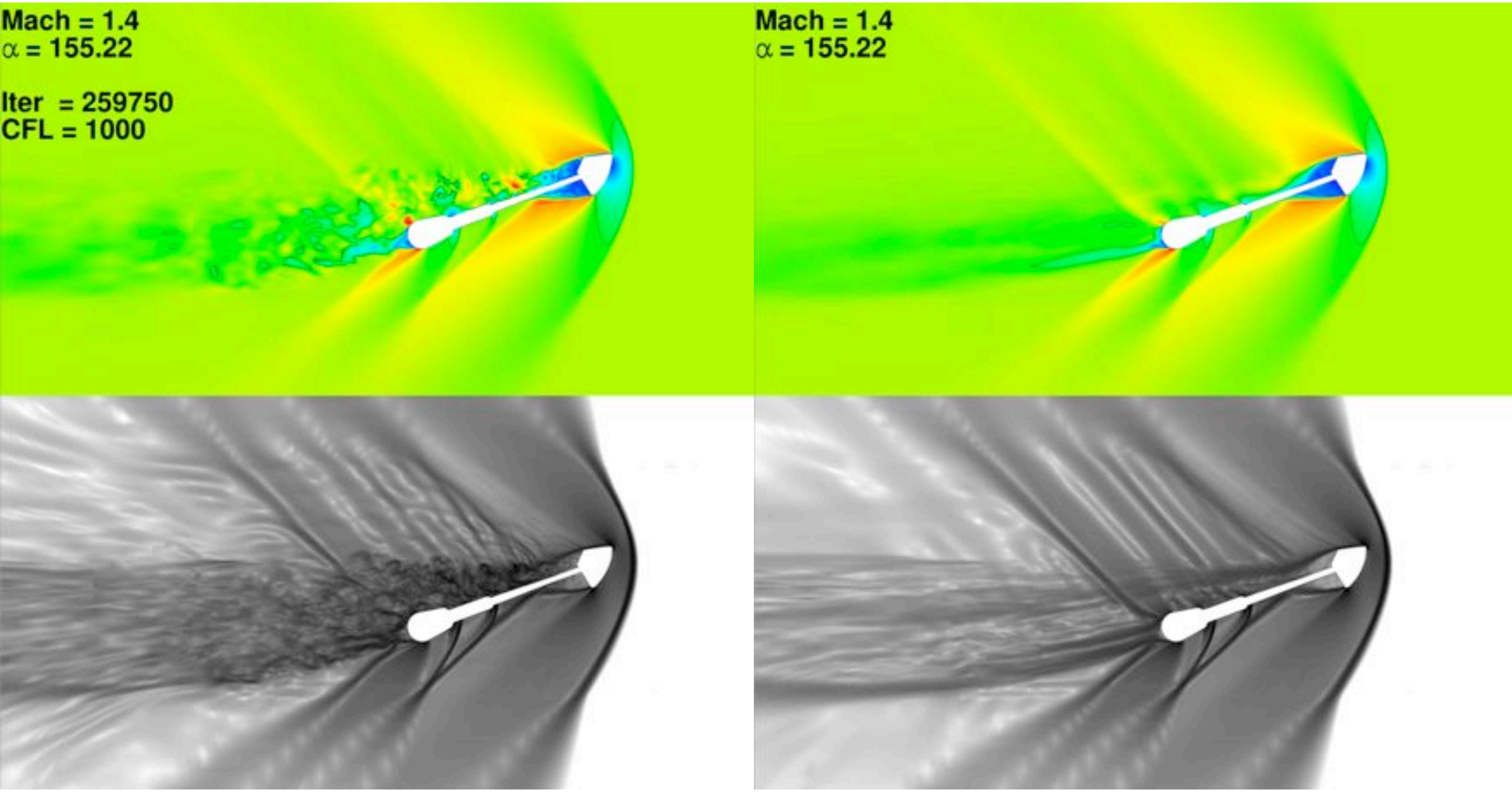
Results - Mach 1.40



Results - Mach 1.40

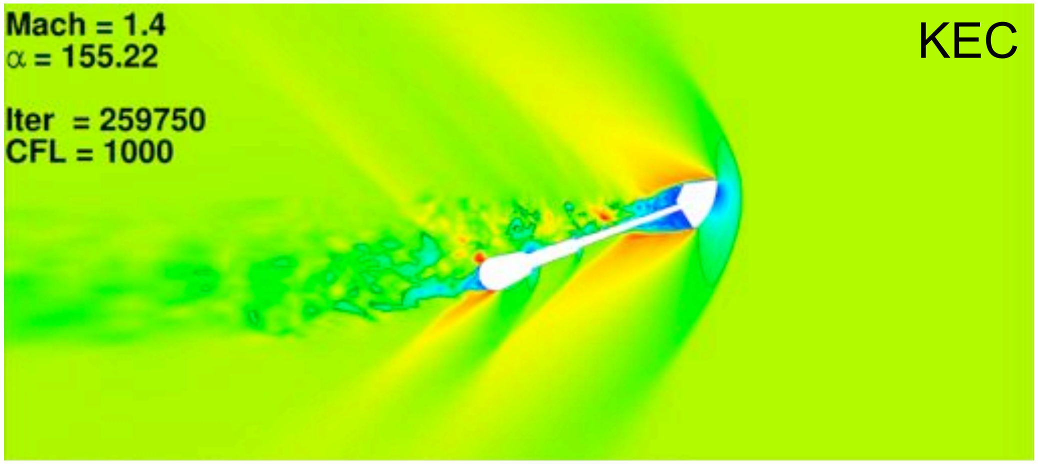
Solutions are very unsteady and so the results were time-averaged in order to compare to similarly time-averaged wind tunnel data.

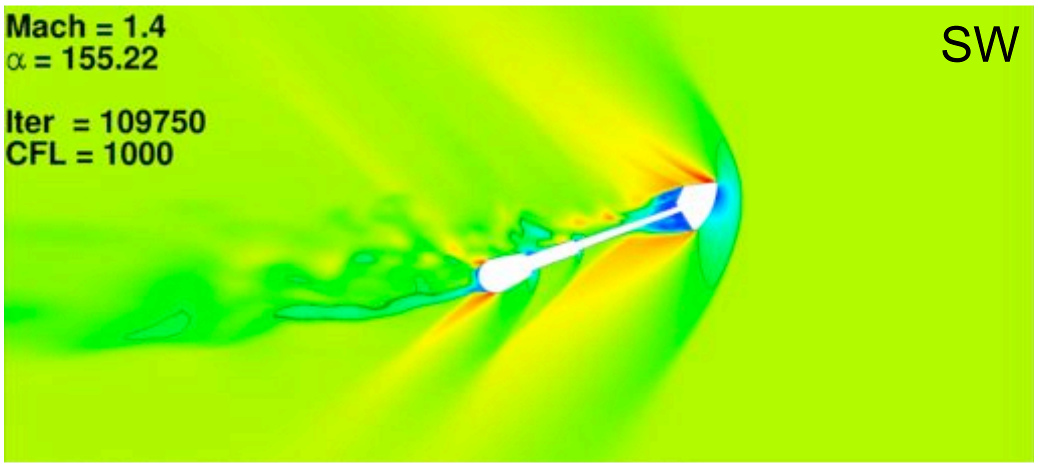
Instantaneous | Averaged

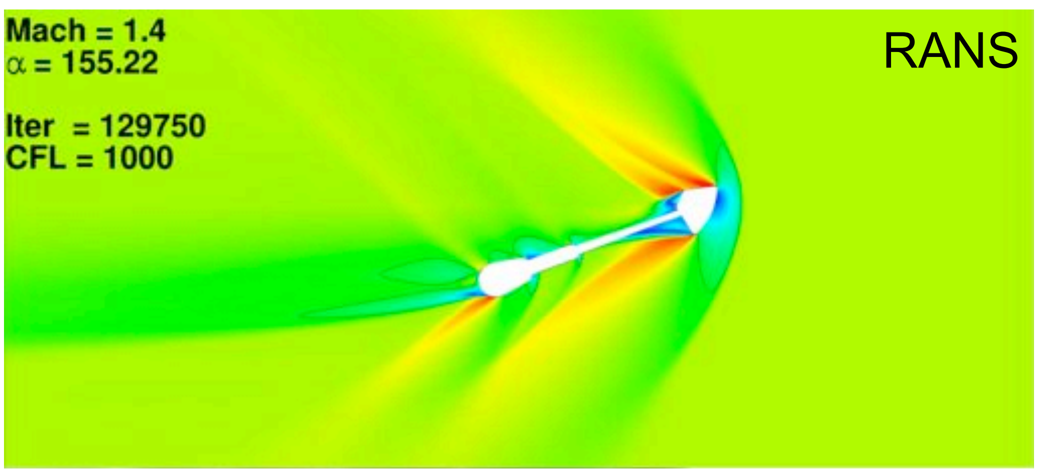


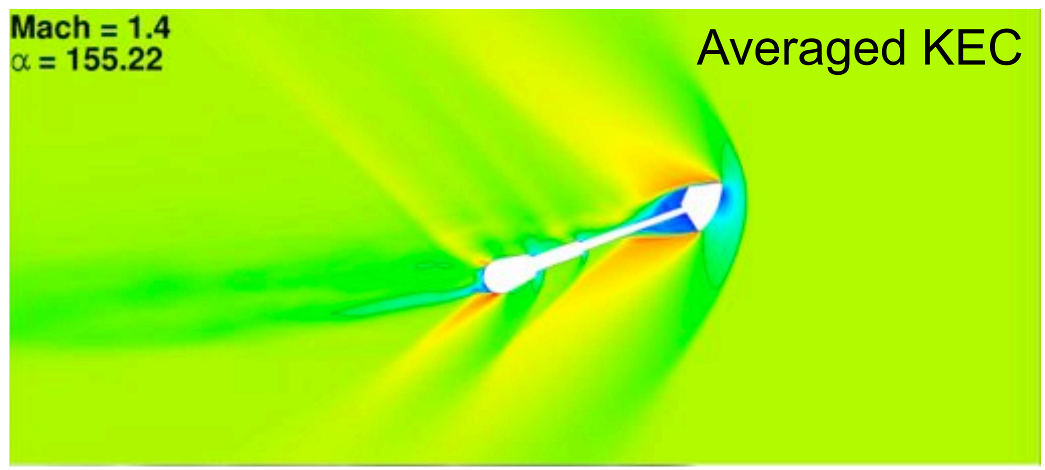
Effects of Numerical Method

- Instantaneous images show qualitative changes between the numerical methods.
- Dissipation grows as we move from KEC → SW → RANS
- There is also a noticeable difference in the flow features on the windward side.

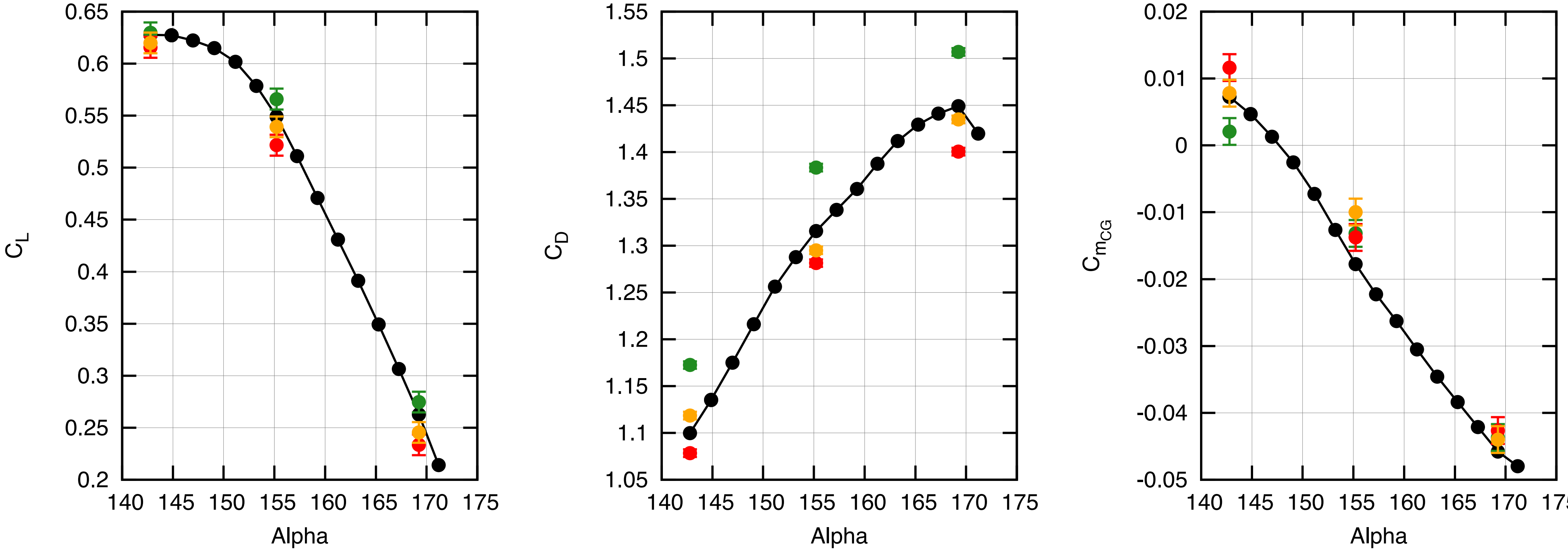




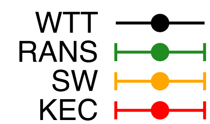




Results - Mach 1.40



Comparisons are good

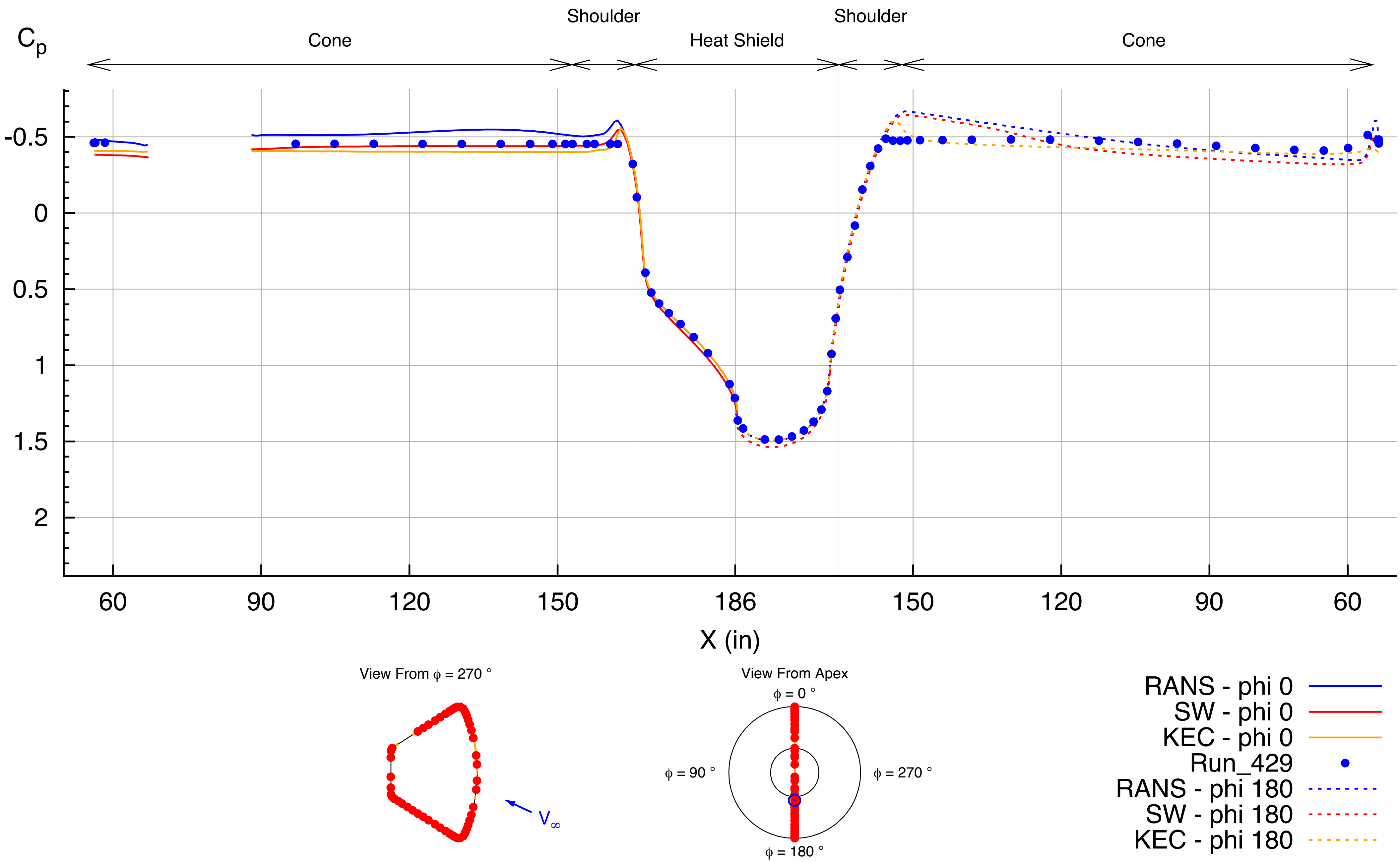


- RANS appears to perform the worst. SW appears to do a bit better than KEC, but both are very close.
- It is not surprising that our comparisons are this strong for this Mach number. The integrated loads are dominated by the forebody pressure and not as sensitive to the modeling in the wake.
- Largest error seen in α=170°, we'll look at the pressure tap data to investigate a bit more.

X_{CG} = 0.680 D

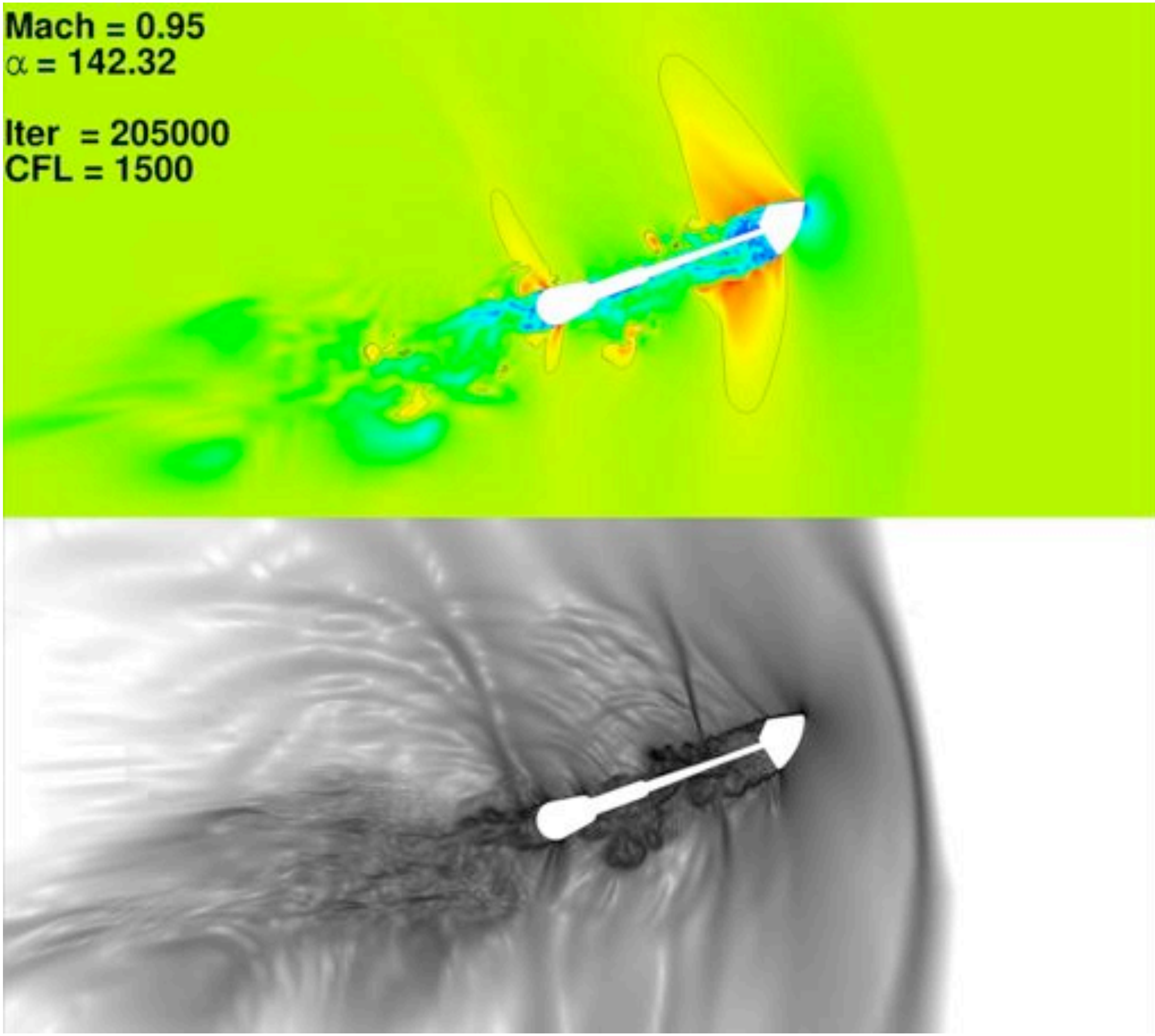
Z_{CG} = -0.045 D

Results - Mach 1.40 α = 155°

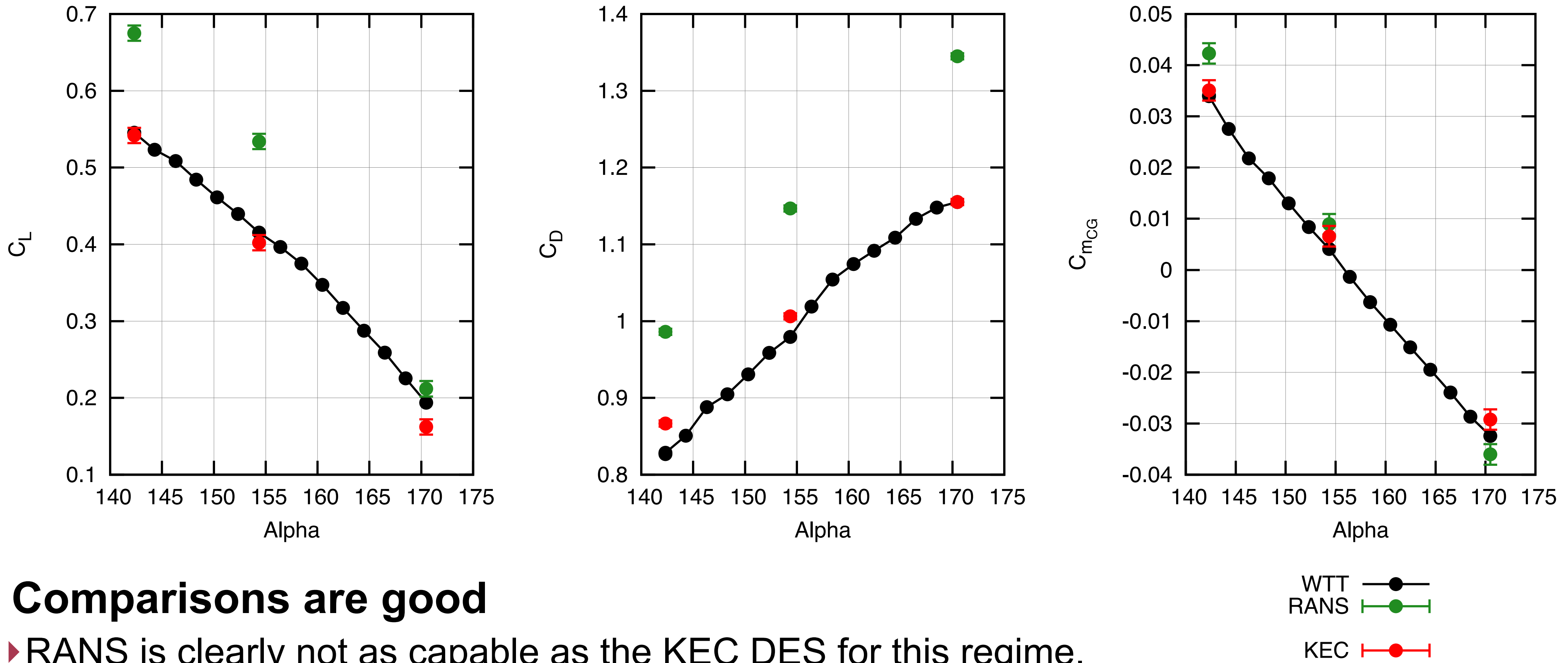


Mach 0.95

Results - Mach 0.95



Results - Mach 0.95

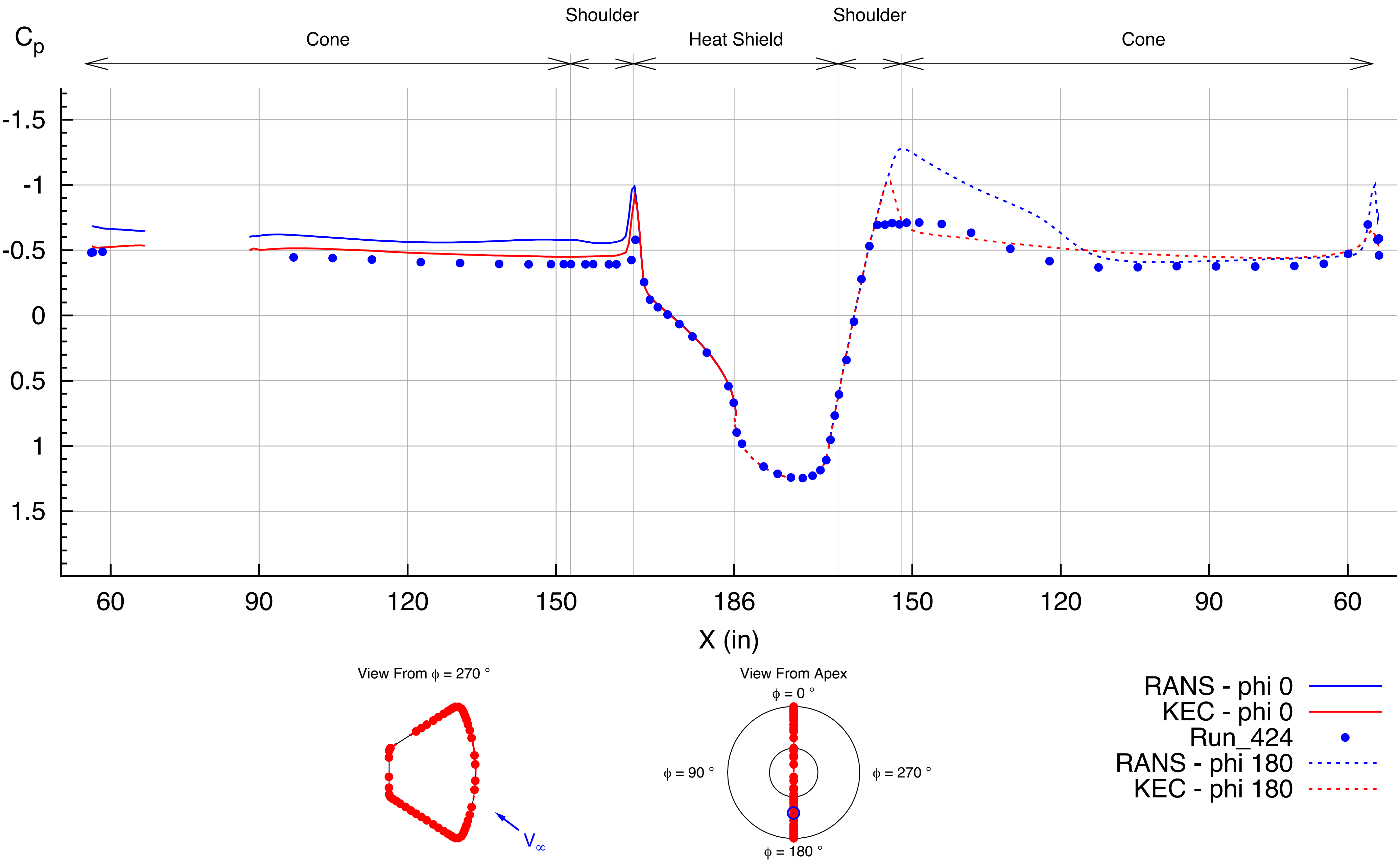


Comparisons are good

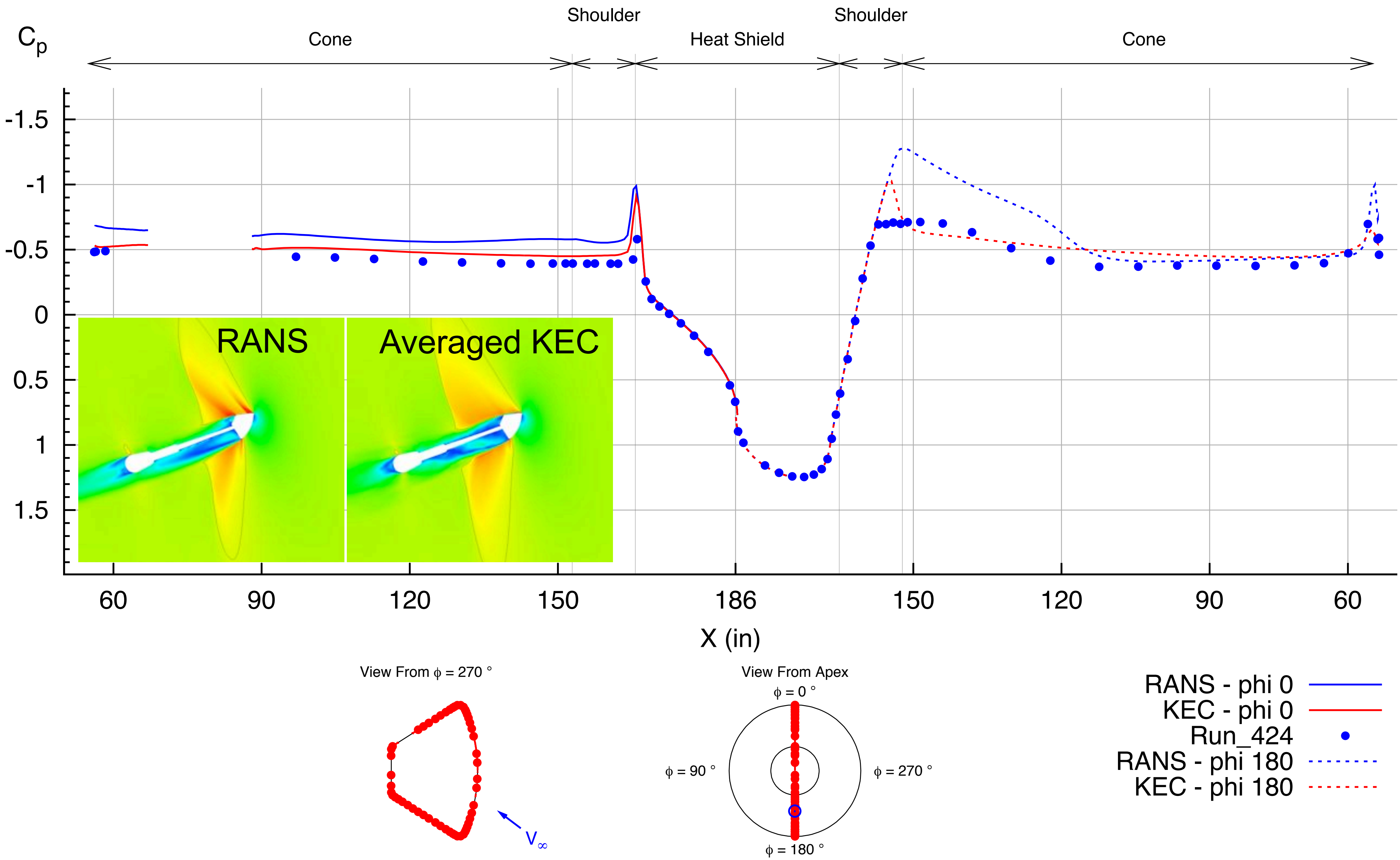
- RANS is clearly not as capable as the KEC DES for this regime. SW was not run.
- Examination of the pressure ports for these cases reveals why RANS has such trouble.

X_{CG} = 0.680 D
Z_{CG} = -0.045 D

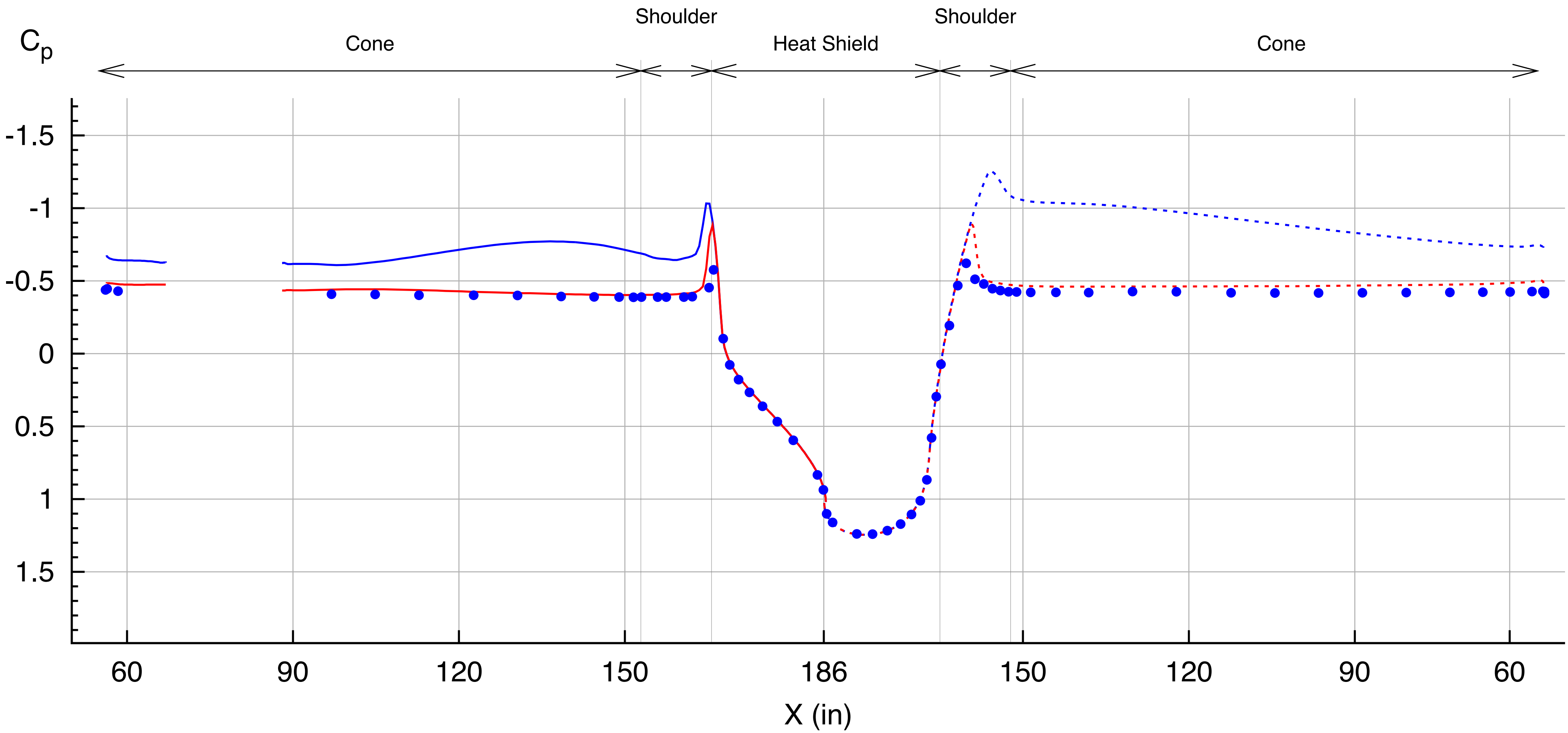
Results - Mach 0.95 α = 140°

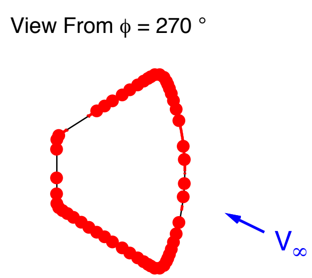


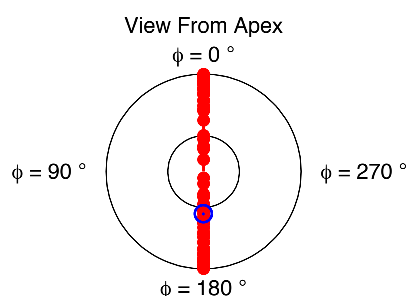
Results - Mach 0.95 α = 140°



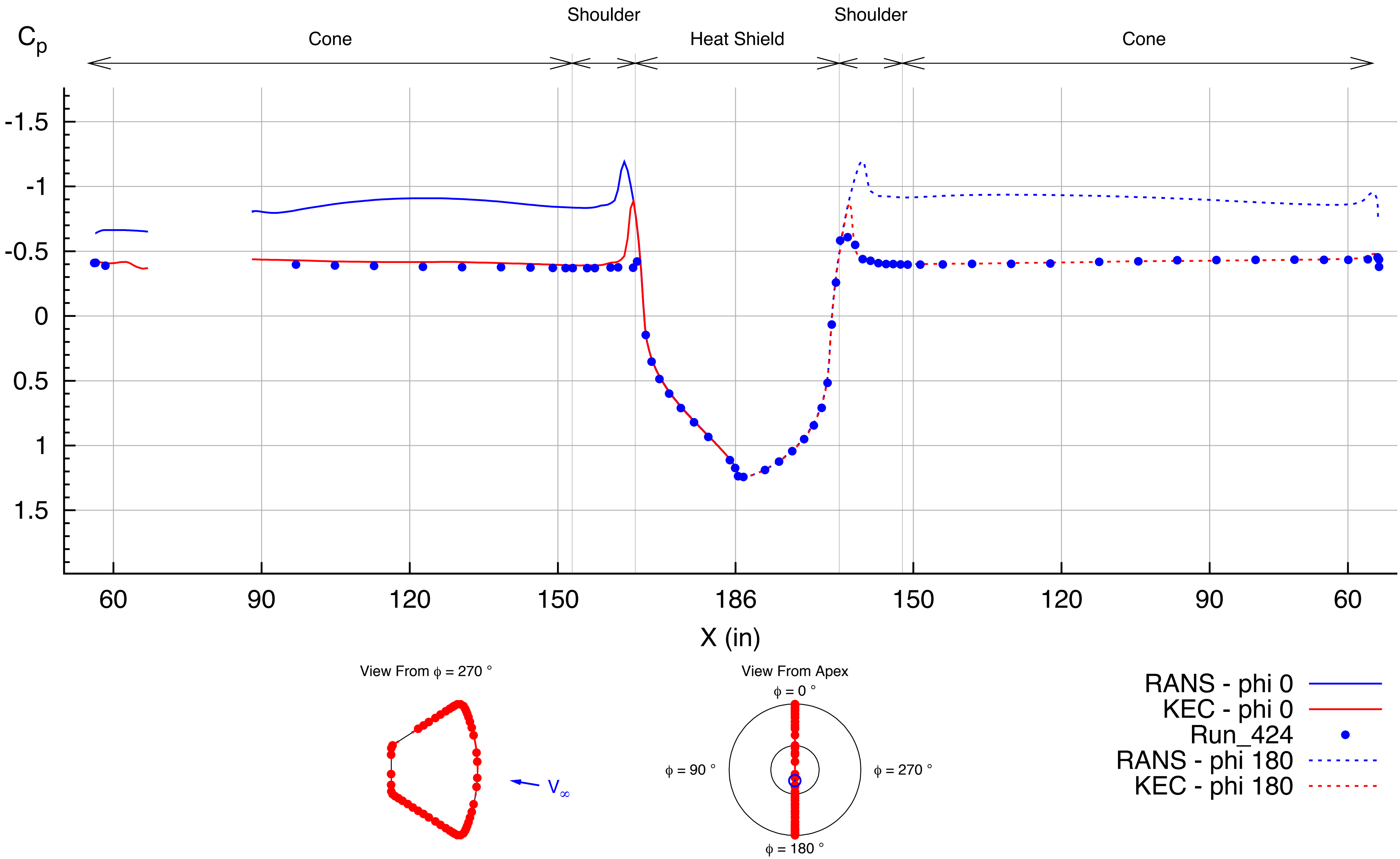
Results - Mach 0.95 α = 140°





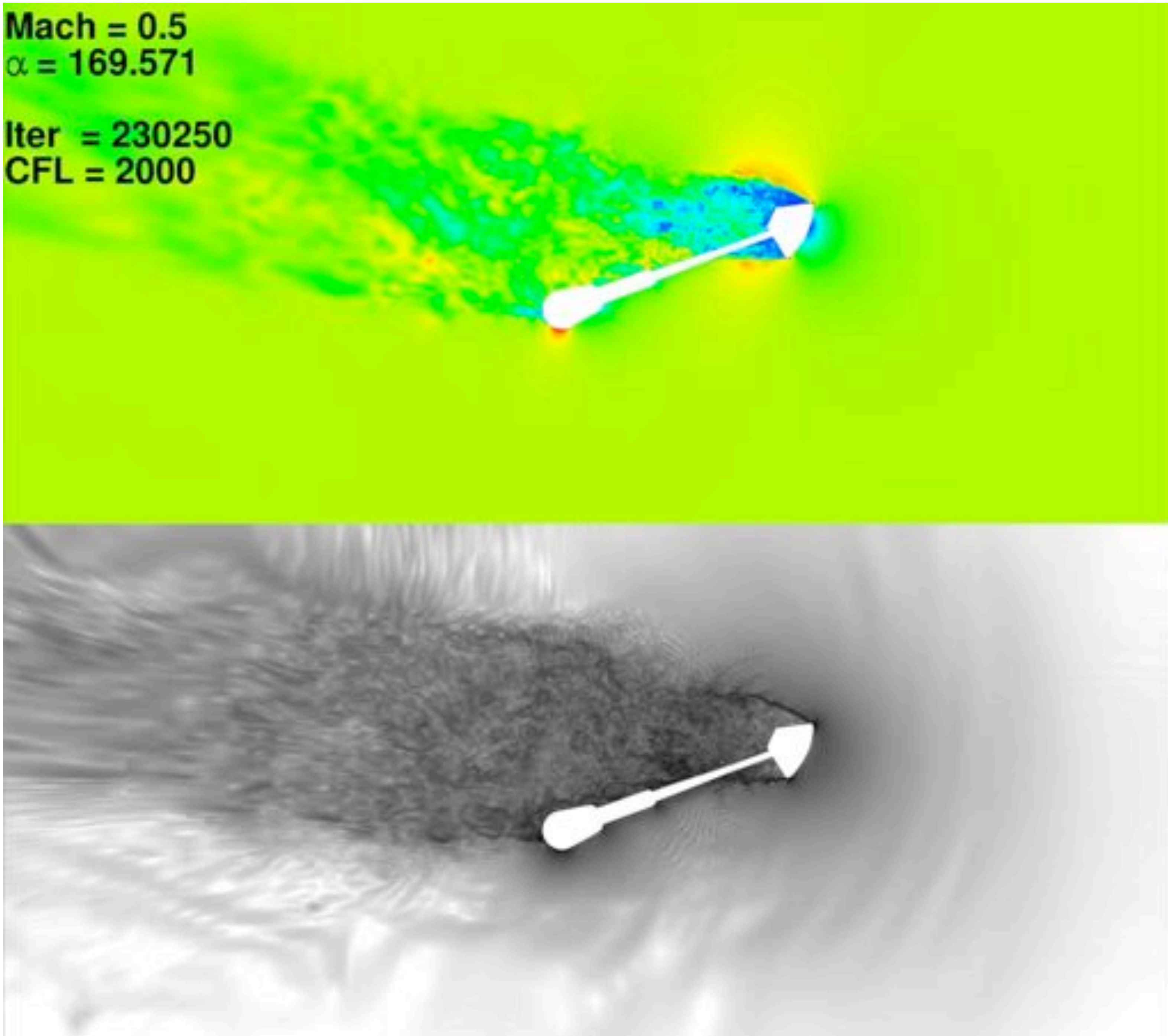


Results - Mach 0.95   α = 140°

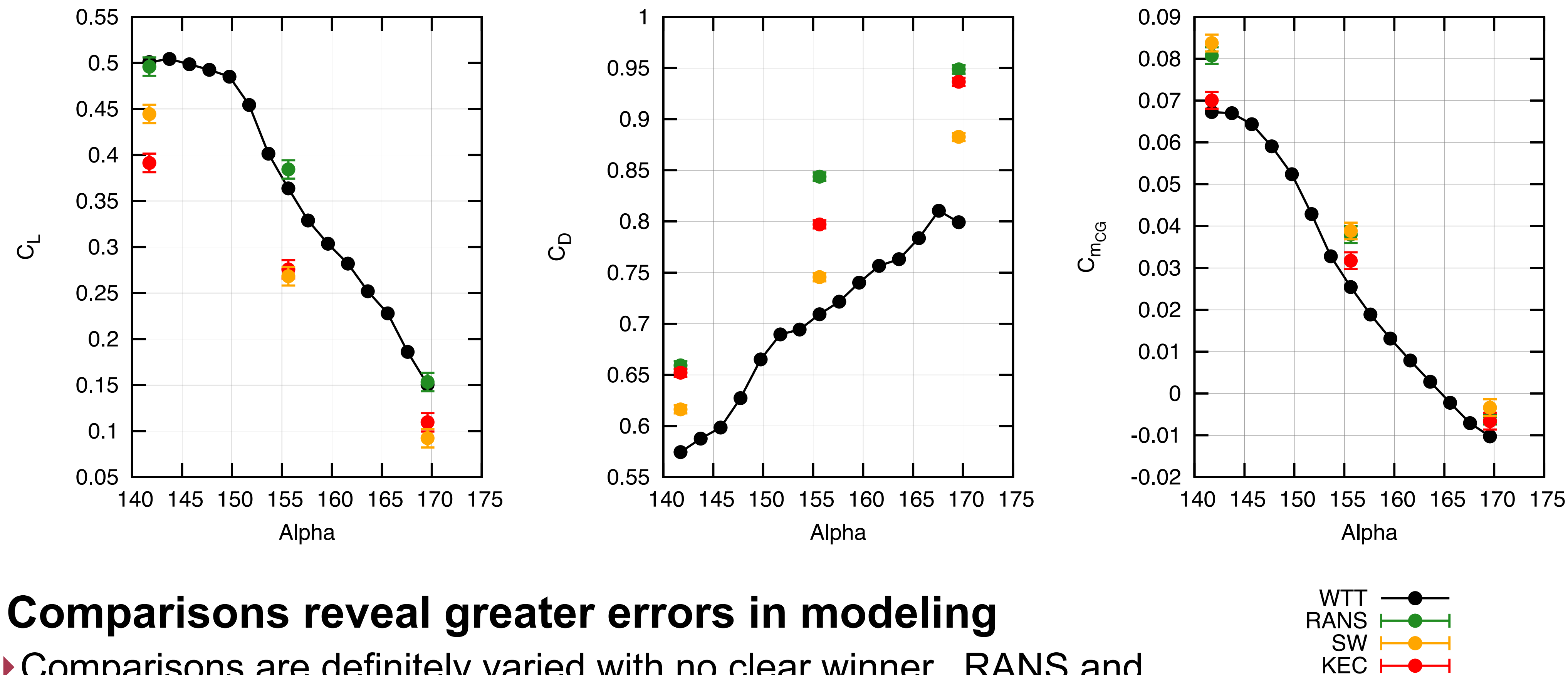


Mach 0.5

Results - Mach 0.50



Results - Mach 0.50



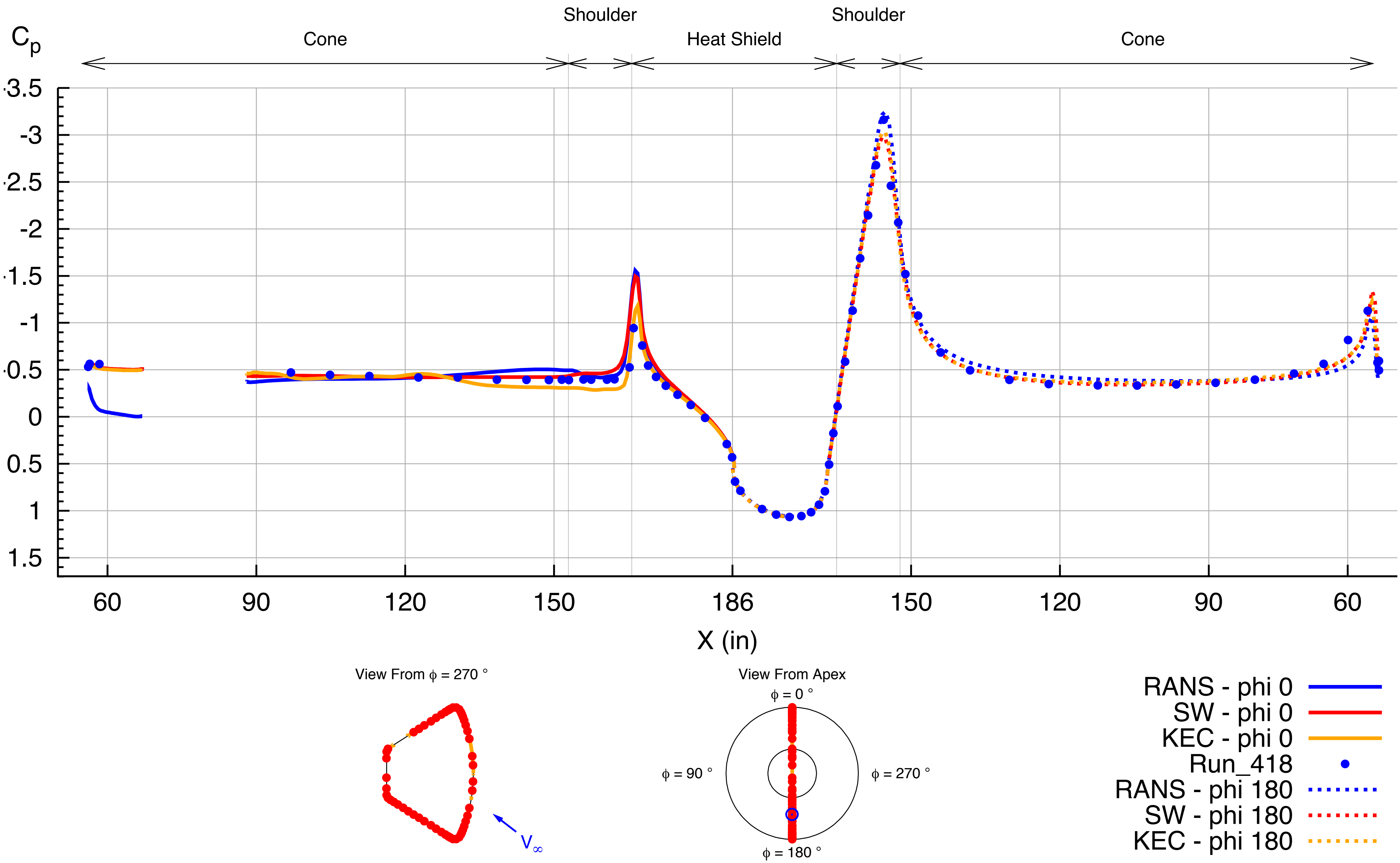
Comparisons reveal greater errors in modeling

- Comparisons are definitely varied with no clear winner. RANS and KEC appear to grab the trend across the forces/moment.
- For a flow this unsteady and with this low of a dynamic pressure, there is a significant contribution from the base flow. Also of interest are large magnitude pressure near the shoulder.
- Pressure port measurements will help illustrate where each model is having troubles.

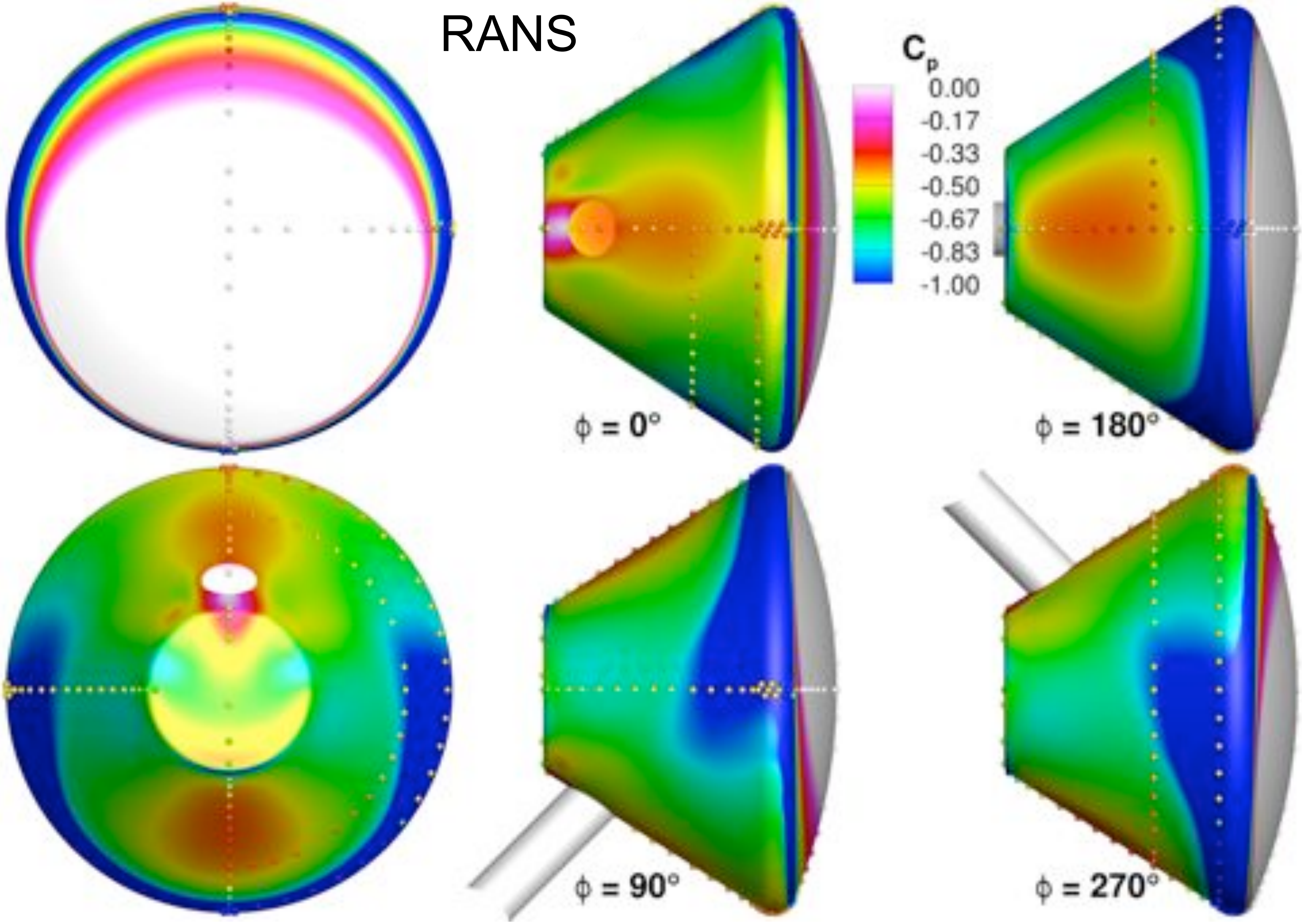
$X_{CG} = 0.680$ D

$Z_{CG} = -0.045$ D

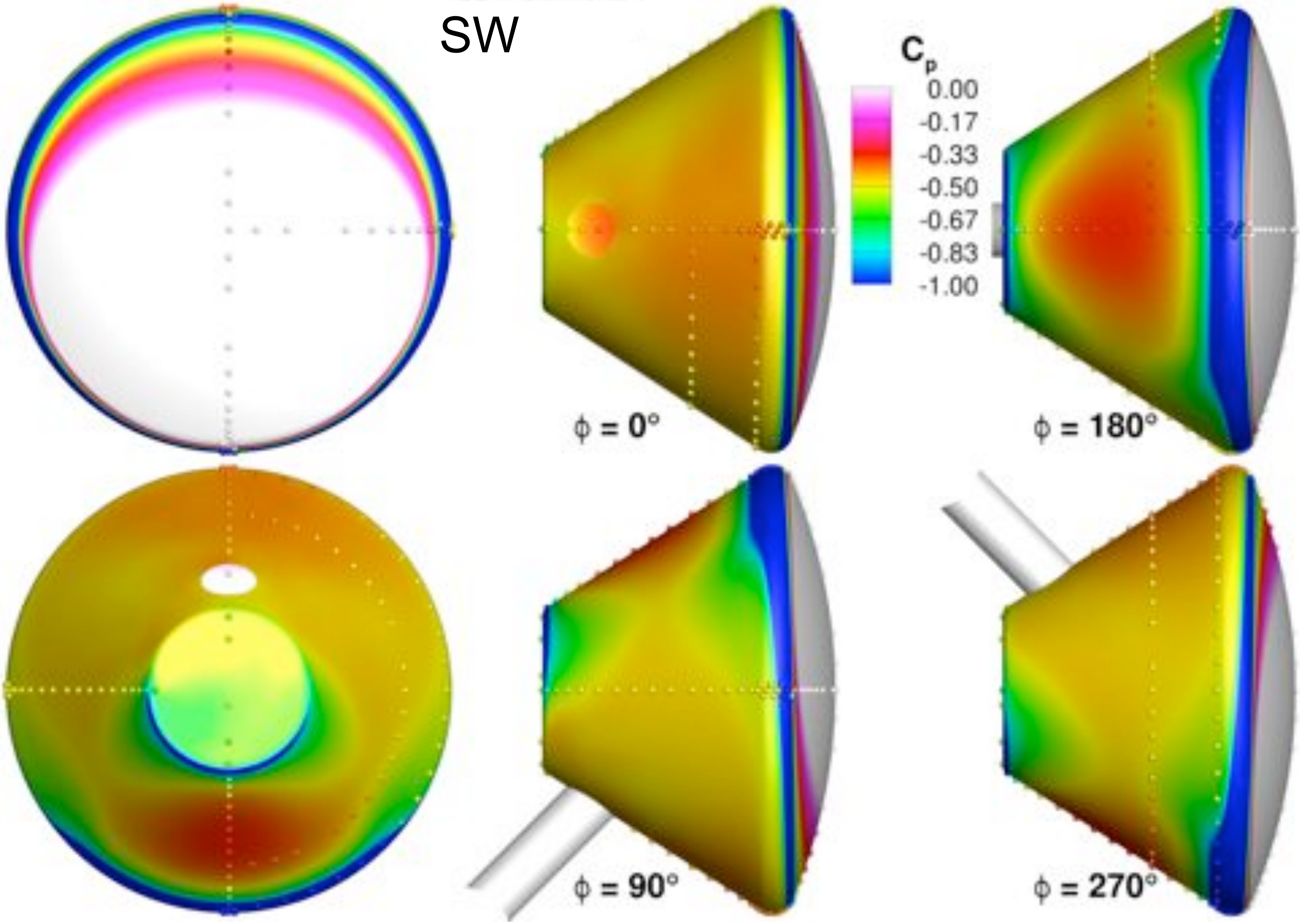
Results - Mach 0.50 α = 140°



Results - Mach 0.50 $\alpha = 140°$

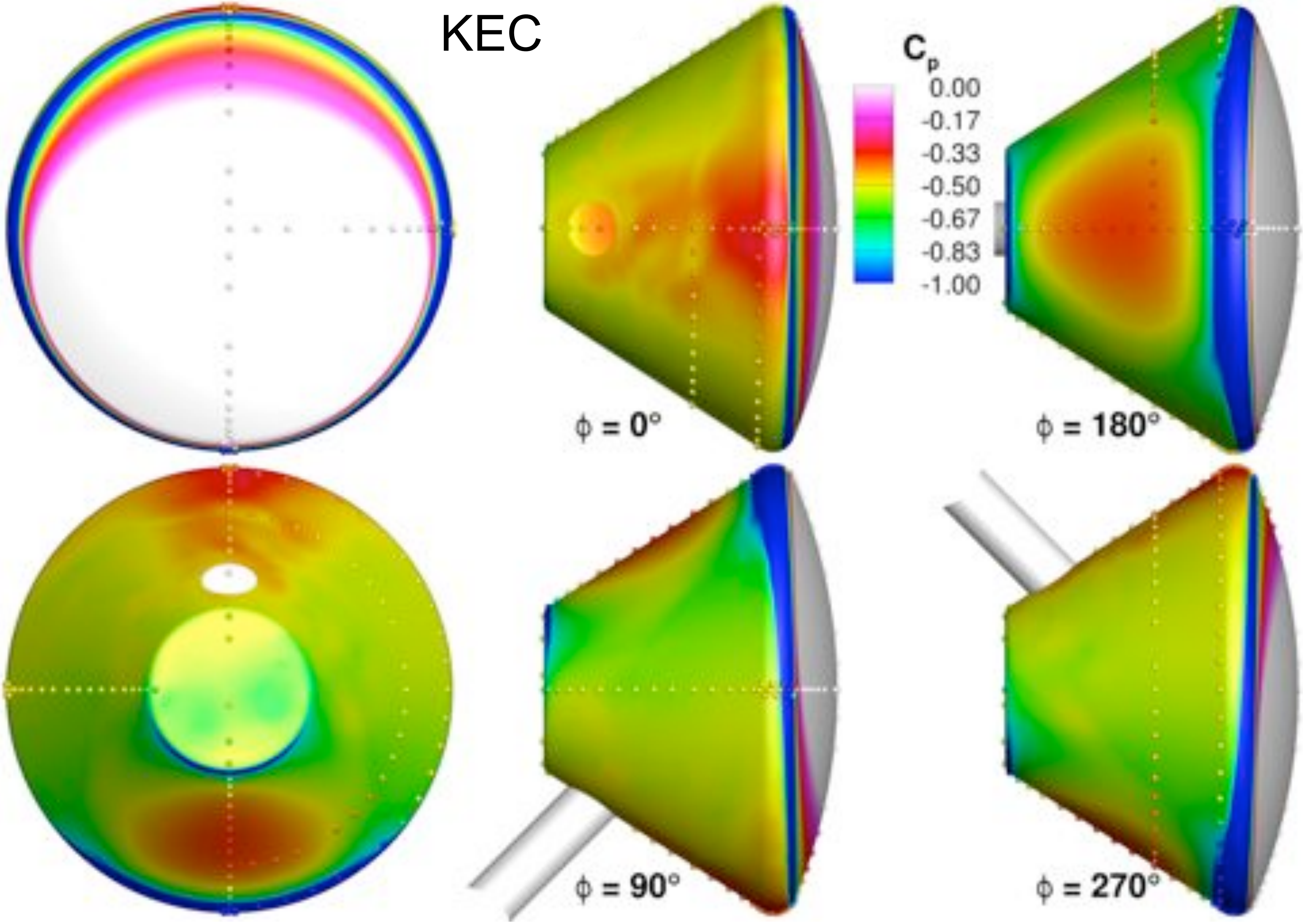


Results - Mach 0.50 α = 140°



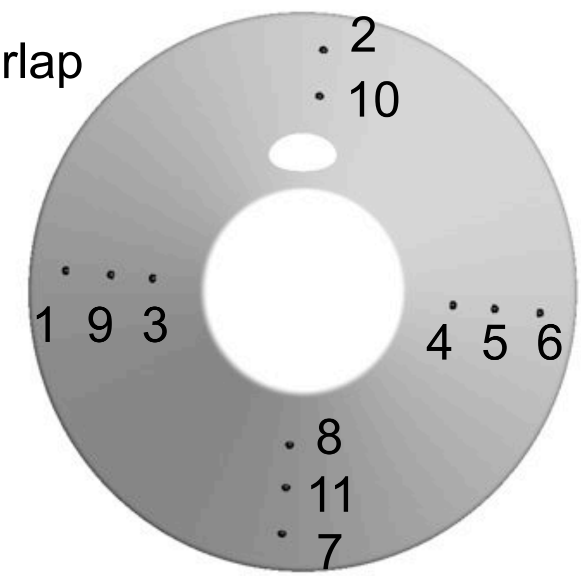
Results - Mach 0.50 α = 140°

KEC

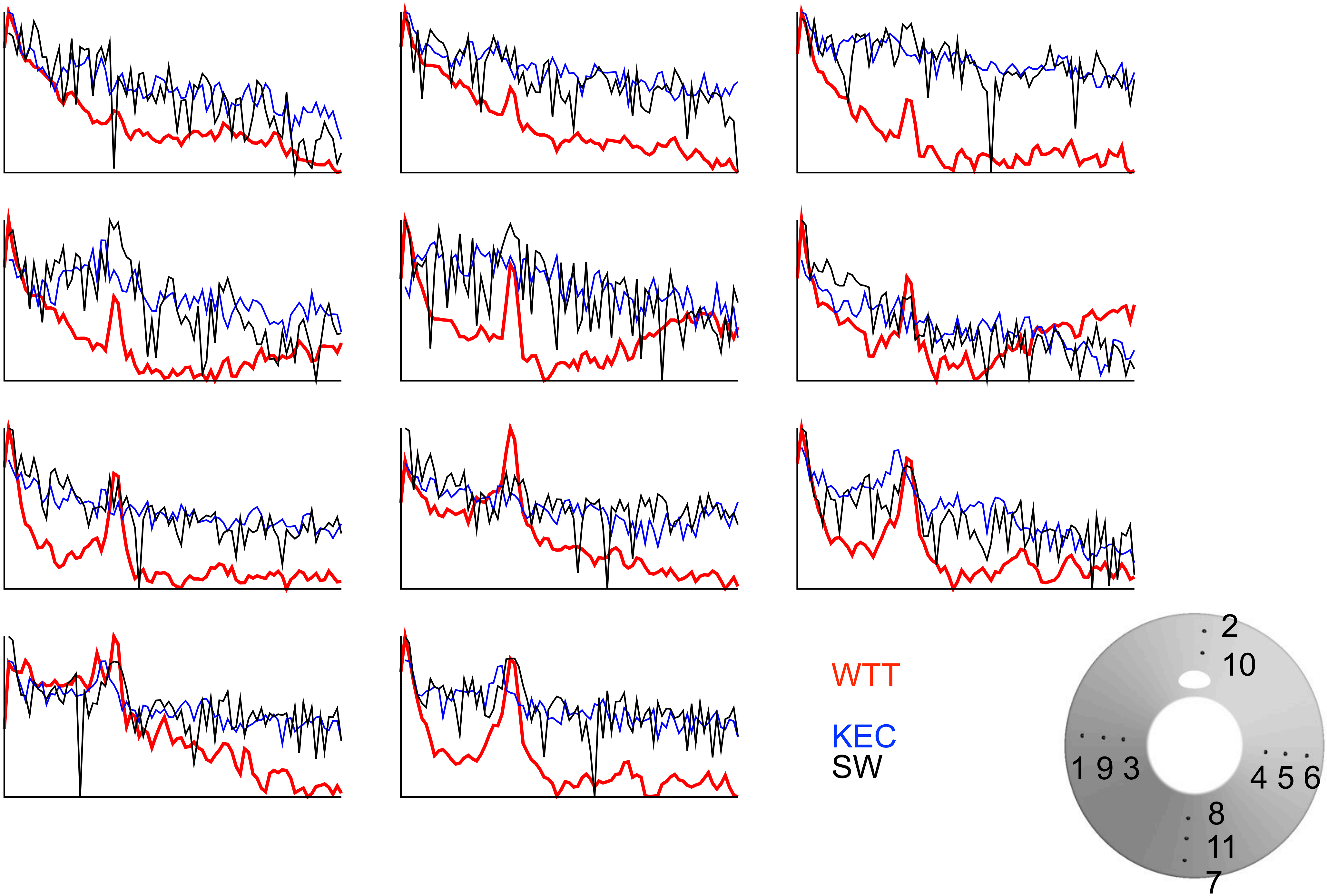


Unsteady Frequency Response

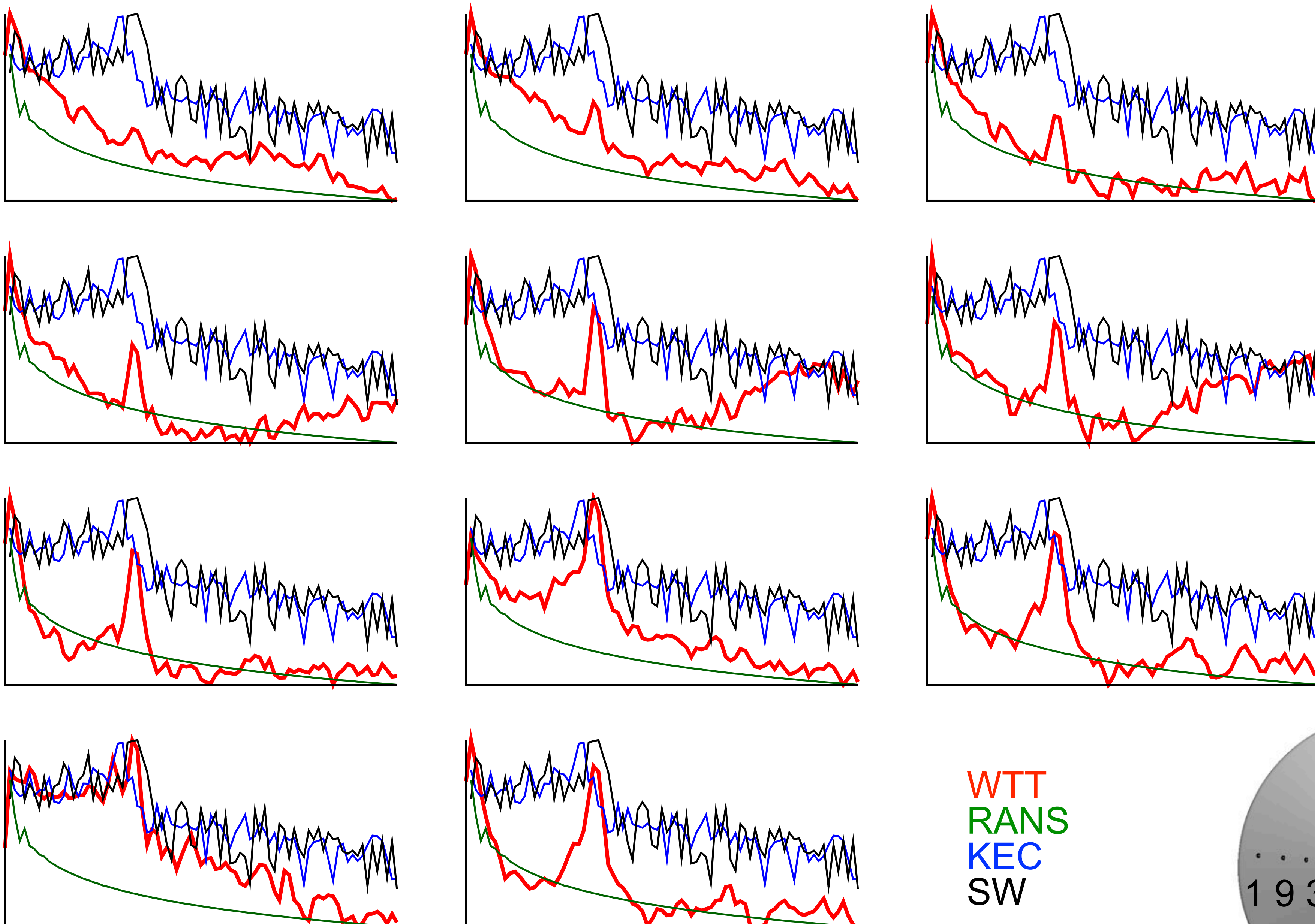
- **Wind tunnel model had 11 taps arranged on the surface of the backshell of the model. These probes recorded data at a rate of 6400 Hz for 6 seconds.**
  - All cases examined in this work included unsteady data.
  - Comparisons revealed that the computational expense necessary to obtain results that were 'statically converged' required significant wall time. For this reason, only one case was examined thoroughly.
- **The Mach 0.50 case at α = 140° was selected for comparison for two reasons:**
  - It was a massively separated case that had a strong response in the wind tunnel data.
  - Integrated loads showed a large spread between the methods examined here and might highlight differences between then.
- **Data was sampled from the CFD at tap locations**
  - Downsampled to 6400 Hz using Welch's Method with 50% overlap
  - 0.2 second intervals (wind tunnel test used 0.2s)
  - Tukey Window used on each interval
- **Frequency response from integrated loads also considered**

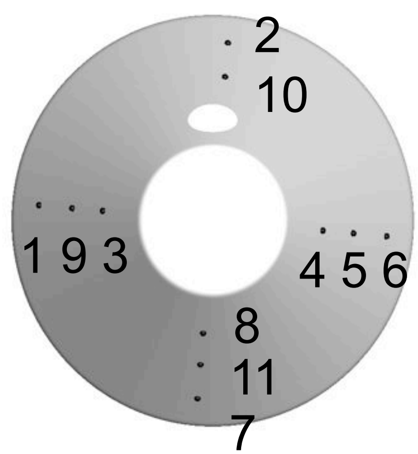


Unsteady Frequency Response - Taps

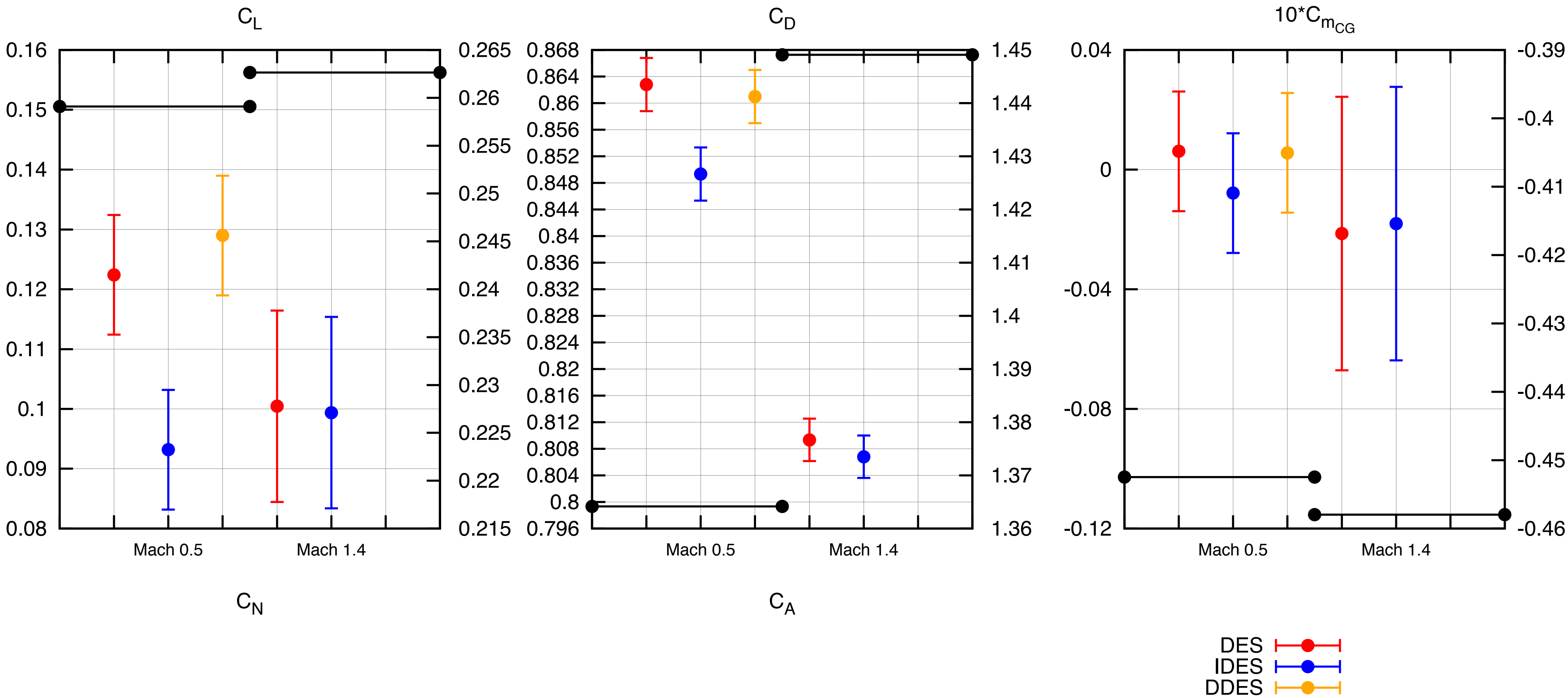


Unsteady Frequency Response - C_m





Varying DES Model



There is a sensitivity to the flavor of DES, but the differences are not substantial and in some cases are negligible.

Conclusions and Further Work

RANS is ill-suited for analysis of these problems. For transonic and supersonic cases, US3D shows fairly good agreement using DES across all cases.

Separation prediction and resulting backshell pressure are problems across all portions of this analysis. This becomes more of an issue at lower Mach numbers:

- Stagnation pressures not as large - wake and backshell are more significant
- Errors on shoulder act on a large area - small discrepancies manifest as large changes

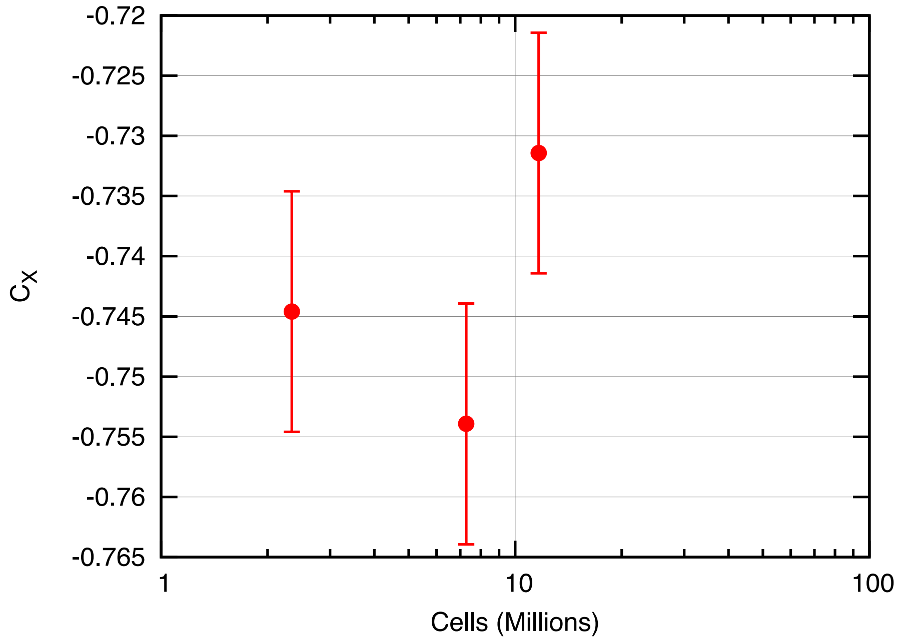
Subsonic comparisons are mixed with regard to integrated loads and merit more attention. Dominant unsteady behavior (wake shedding) resolved well, though.

Further work:

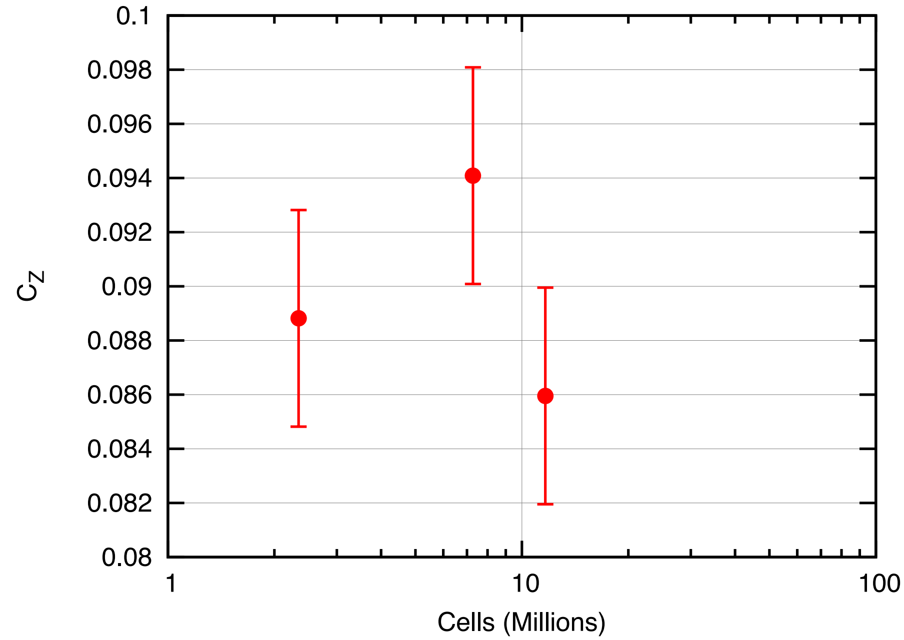
- Evaluate the effect of other turbulence models on separation prediction
- Use more advanced tools to look into improvements that might be made with grid quality
- Investigate transition and its effect on separation

BACKUP

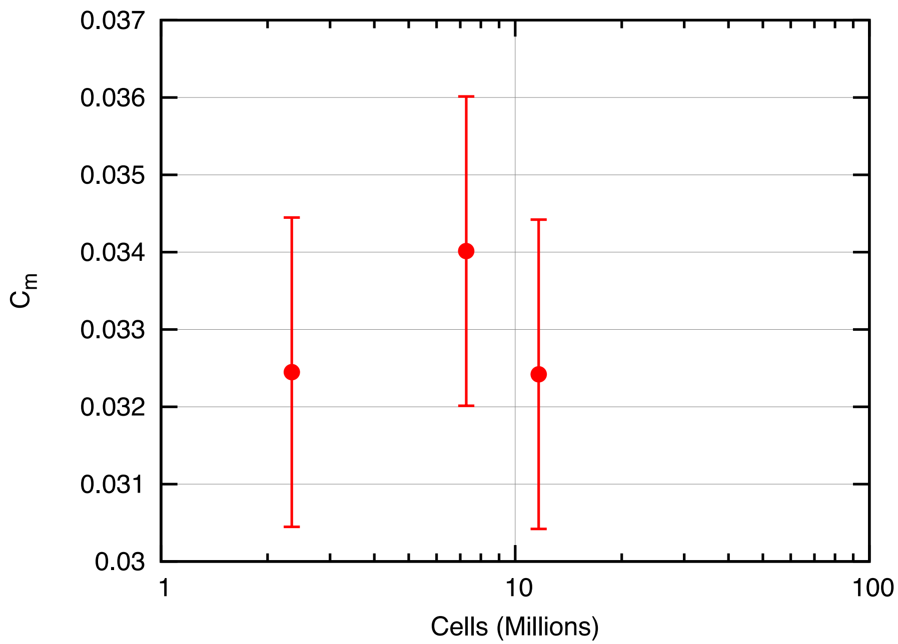
Mach 0.5



-0.72
-0.725
-0.73
-0.735
-0.74
-0.745
-0.75
-0.755
-0.76
-0.765
C_X
1
10
100
Cells (Millions)

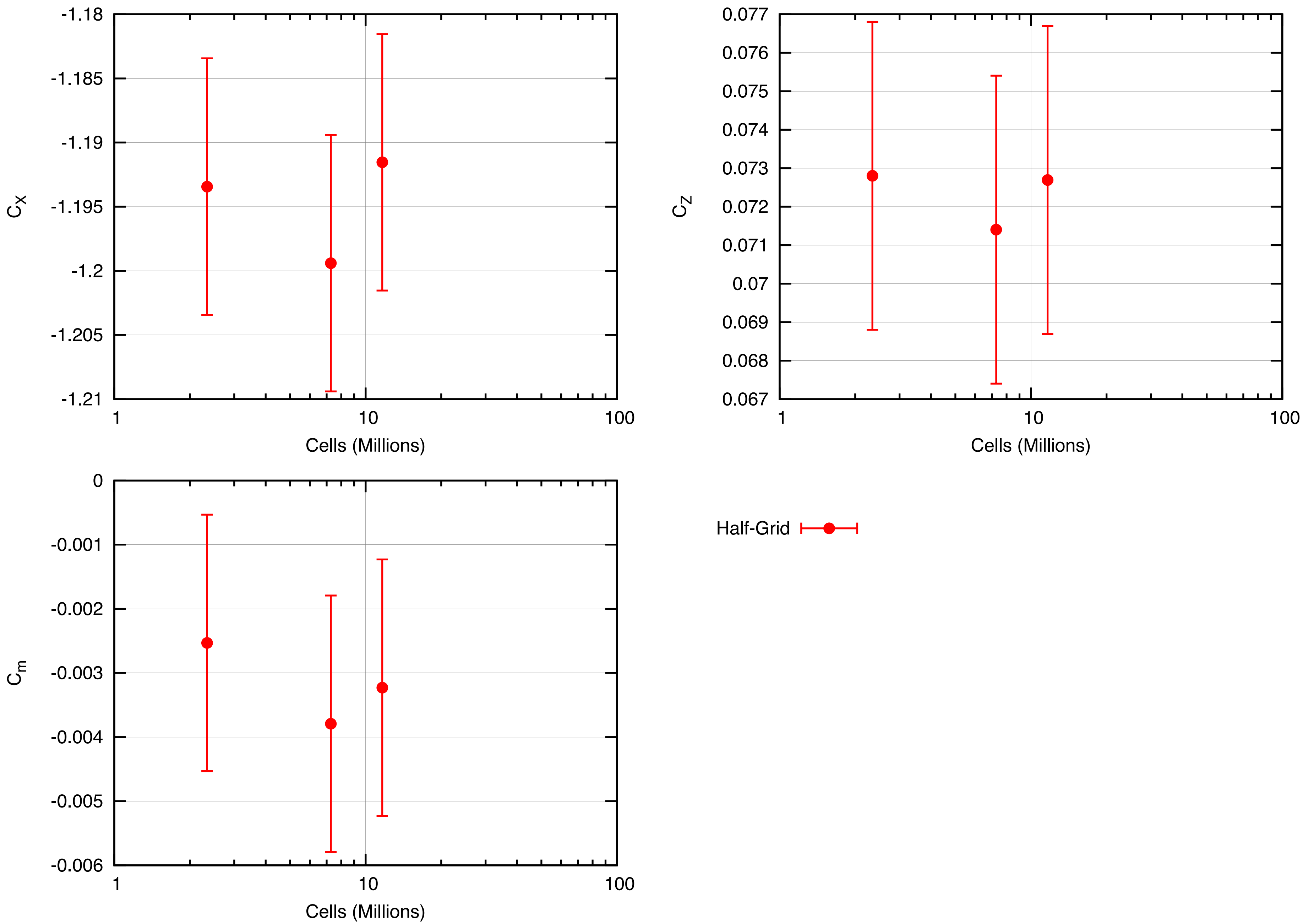


0.1
0.098
0.096
0.094
0.092
0.09
0.088
0.086
0.084
0.082
0.08
C_Z
1
10
100
Cells (Millions)



0.037
0.036
0.035
0.034
0.033
0.032
0.031
0.03
C_m
1
10
100
Cells (Millions)
Half-Grid

Mach 0.95



-1.18
-1.185
-1.19
-1.195
-1.2
-1.205
-1.21
C_X
1
10
100
Cells (Millions)
0.077
0.076
0.075
0.074
0.073
0.072
0.071
0.07
0.069
0.068
0.067
C_Z
1
10
100
Cells (Millions)
0
-0.001
-0.002
-0.003
-0.004
-0.005
-0.006
C_m
1
10
100
Cells (Millions)
Half-Grid